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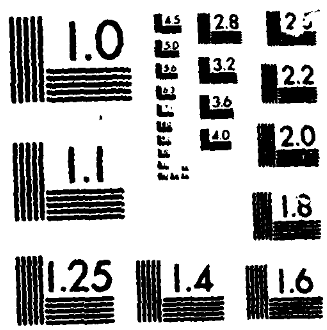

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OBJECTIVE ANALYSIS OF TROPICAL CYCLONE INTENSITY, STRENGTH, AND SIZE USING ROUTINE AIRCRAFT RECONNAISSANCE DATA

A Thesis

by

CHARLES BAYNARD STANFIELD

Submitted to the Graduate College of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 1986

Major Subject: Meteorology

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STRENGTH, AND SIZE USING ROUTINE AIRCRAFT RECONNAISSANCE DATA

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ABSTRACT

Objective Analysis of Tropical Cyclone Intensity, Strength, and Size Using Routine Aircraft Reconnaissance Data. (May 1986)

Charles Baynard Stanfield, B.S., Florida State University

Chairman of Advisory Committee: Dr. Aylmer H. Thompson

The feasibility of objectively analyzing routine aircraft reconnaissance data for the purpose of quantifying tropical cyclone intensity, strength, and size is examined. A computer program is developed which may be used in near real time or after the fact to evaluate localized pressure/wind relationships in the tropical cyclone environment. This program compensates for the system motion and the relative position of the point of observation relative to the vortex center location at flight level and at the surface (thus accounting for the vertical tilt of the center). A representative set of data is obtained over a 13 month period for the entire spectrum of storms from tropical depression to super typhoon. These data are used to try to establish empirical pressure/wind relationships and a means of determining effective storm size. It is shown that a program of this nature may be used with gradient wind and pressure gradient relationships to evaluate intensity and strength and to define storm size, provided adequate data are available at sufficient distances from the center.

DEDICATION

This thesis is dedicated to my Father, the late C. M. Stanfield Jr. Whereas this thesis will attempt to educate, he has already succeeded.

ACKNOWLEDGEMENTS

The writer would like to acknowledge the help and support of his committee. I am very grateful to the Department of Meteorology for the generous offering of its resources to this effort which was independent of contract or grant funding. In particular, I would like to express my thanks to Dr. Aylmer H. Thompson who provided his comments and guidance.

Sincere thanks are extended to Mr. John Walsh and Mr. Louis Westphal of OL-A, USAFETAC for collecting the data used herein.

Finally, I would like to thank my family for their patience during these years of study, to my sister, Suzanne Thatcher, for doing much of the typing, and especially to my wife who gave me the encouragement to finish.

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LIST OF SYMBOLS

A, B	Scaling parameters in the Holland hurricane/typhoon wind and pressure profile equation.
C	Hypsometric constant.
d	Diameter of a tropical cyclone determined by analyzing the outermost closed surface isobar.
dp, Δp	Change in pressure between observations.
dr, Δr	Distance over which pressure gradient is measured between observations, measured along or projected onto a common radius.
f	Coriolis parameter.
g	Gravitational constant.
H_{70}	Height of the 70 kPa pressure surface.
H_{100}	Height of the 100 kPa pressure surface.
M	Median value.
p	Pressure at radial distance r.
p_c	Minimum sea level pressure at the tropical cyclone center.
p_n	Approximation of the environmental sea level pressure surrounding a tropical cyclone.
p_o	Sea level pressure.
p_s	Surface center's pressure level (see Fig. A-4).
p_u	Pressure at flight level (usually 70 kPa).
p'	Tropical cyclone's outermost closed isobar value.
R	Universal gas constant.
R_d	Gas constant for dry air.
RH	Relative humidity.
r	Radial distance from the center.
r_a	Adjusted radial distance to the midpoint for which the adjusted innermost pressure gradient applies (see Fig. 6).

LIST OF SYMBOLS (Continued)

r_g Distance of supplemental ship report from the surface vortex center.

r_o Initial innermost radius between the tropical cyclone center and the first observation point over which pressure gradient is measured (see Fig. 6).

r_p Radius of the minimum pressure center within a tropical cyclone (see Fig. 6).

r_s Distance of an observation from the surface vortex center.

r_u Distance of an observation from the flight level vortex center.

r' Storm radius determined by p'.

r'_o Adjusted distance over which the innermost pressure gradient of a tropical cyclone is measured.

T Ambient temperature.

T_d Dew point temperature.

T_v Virtual temperature.

$\overline{T}_v$ Mean virtual temperature.

t Time.

V_{ah} Sustained one minute maximum surface wind computed by the method of Atkinson and Holliday.

V_c Cyclostrophic wind.

V_{cbs} Maximum surface wind computed using the program prepared by the author.

V_{gr} Gradient wind.

V_i Instrumentally observed maximum winds at flight level.

V_m Maximum surface wind speed in knots used by original authors of tropical cyclone central pressure and maximum wind relationships (this included peak wind gusts) (see Chapter III).

V_o Maximum surface winds observed by aircraft observers.

LIST OF SYMBOLS (Continued)

V_s — Sustained one minute maximum surface wind in knots used in the 1960's to define tropical cyclone central pressure and maximum wind relationships.

w — Mixing ratio.

$\overline{X}$ — Mean value.

β, β' — Angle of transposition.

Φ — Latitude in degrees.

ϕ — The angle for positioning observations in a cylindrical coordinate system centered on the cyclone vortex.

LIST OF ACRONYMS

AROCI	Average radius of the outermost closed isobar.
AROCSI	Average radius of the outermost closed symmetrical isobar.
ASW	Average surface wind.
FLHG	Flight level height gradient.
IPG	Innermost pressure gradient.
MSW	Maximum surface wind.
SLPG	Sea level pressure gradient.

CHAPTER I

INTRODUCTION

During the early years of tropical cyclone reconnaissance, the lack of technology limited the ability of observers aboard reconnaissance aircraft to collect meaningful information in the periphery of the tropical cyclone. The rather undisciplined approach of reconnaissance procedures led scientists using the data to use only a few variables (i.e., minimum sea level pressure) in developing their equations and models of tropical cyclone structure.

With advances in technology, the quality and density of data in the tropical cyclone environment increased. The content, format, and collection of routine tropical cyclone reconnaissance information have become more systematic and disciplined in recent years. Still, except for data collected by the United States National Oceanic and Atmospheric Administration Research Flight Facility, little use is made of peripheral data that are being collected on routine reconnaissance missions. With the use of these data, the structure of specific tropical cyclones in various stages of development can be understood better. In addition to the intensity (maximum sustained wind of the storm), the effects of overall strength (average wind speed) and size (radius of the circulation) of a specific storm can be determined more accurately in real time if concrete relationships with pressure gradient are established.

The citations on this and the following pages follow the style of the Monthly Weather Review.

Estimates of surface winds by observers in aircraft flying at the 70 kPa pressure level (approximately 3000 m above sea level) and even at low level (less than 500 m above sea level), have been neglected as reliable depictions of the actual wind profile of the tropical cyclone. Reasons for this include: 1) individual observer misinterpretation, 2) observer inexperience, 3) observations taken at non-specified levels for surface winds, 4) observations taken in poor visibility conditions, 5) the relatively broad classifications of surface wind speed, and 6) the inability to see the entire sea surface area of the tropical cyclone. This last reason includes the factors of intervening clouds and restricted flight in the area of the storm. Dynamically, the maximum winds are associated with the eye wall cloud and convective feeder bands. In these regions, the sea surface usually is obscured by cloud, and large amounts of ocean water are picked up and carried in the air. Because of these obstacles, maximum surface wind may be estimated incorrectly by visual observation. Because Doppler radar may track airborne moisture as well as the sea surface, the flight level wind may be estimated incorrectly by instruments.

Even though problems still exist with surface wind estimates by aircraft observers, more accurate definitions of wind speeds below 67 m s^{-1} have resulted because of the years of experience since the first reconnaissance missions were flown. This study will bring out the weaknesses and strengths of using these data, and recommendations will be offered as to how to improve the usefulness of the data.

CHAPTER II

OBJECTIVE

This research examines the potential of routine aircraft reconnaissance observations to determine objectively tropical cyclone intensity, strength, and size characteristics. The term "routine" refers to those means of data collection used on U.S. Air Force aircraft reconnaissance missions of the late 1970's and early 1980's.

The primary objective is to derive empirical relationships (if possible) that relate the observed 70 kPa height gradient or the surface pressure gradient to the intensity, strength, and size characteristics of tropical cyclones at the earth's surface. First, relationship of the 70 kPa height gradient or sea level pressure gradient to the observed winds is determined using a relatively coarse distribution of aircraft observations centered in relation to the vortex center. Second, the gradient wind is computed using the height/pressure gradients and compared to the observed winds. The effects of system motion and vertical tilt of the vortex center are accounted for in the program. A determination is made of which method (the empirical relationships of observed winds and pressure gradients or simply the gradient wind relationships) is best in defining the location and magnitude of the maximum wind zone (intensity) and the overall wind speed profile (strength) of tropical cyclones. In addition, a method is examined for defining storm size using an assumed pressure profile in data sparse areas.

The results are interpreted in light of the data gathering techniques of the past as well as the future, and recommendations are made for upgrading of the aircraft reconnaissance platform.

CHAPTER III

BACKGROUND

The endeavor to establish a relationship between tropical cyclone winds and pressure began in 1939. Using data from Pacific typhoons, Takahashi (1939) was the first to develop the rather fundamental relationship,

$$V_m = 13.4\ (p_n - p_c)^{0.5} \quad , \tag{1}$$

from the cyclostrophic wind equation. This equates the maximum surface wind speed in knots (V_m) to the difference between the cyclone's minimum sea level pressure (p_c) and the environmental pressure (p_n) in millibars. Most research since Takahashi has been only to modify this relationship.

McKnown (1952) and his assistants used aircraft reconnaissance data from Pacific typhoons and further modified the equation. His equation is

$$V_m = (20 - \Phi/5)\ (1010 - p_c)^{0.5} \quad , \tag{2}$$

where Φ is latitude in degrees.

Fletcher (1955) used data collected by the Corps of Engineers in the hurricane of 26-27 August, 1949 at Lake Okeechobee, Florida to revise Takahashi's equation, obtaining

$$V_m = 16\ (p_n - p_c)^{0.5} \quad . \tag{3}$$

Here p_n was defined as the environmental pressure at the "outer edge" of the cyclone and was assumed to be either 1010 mb or 2-3 mb higher than the outermost closed surface isobar, as analyzed on the surface synoptic chart.

Prior to 1956, equation development was based upon the peak gusts of the storm rather than the sustained (one minute average) surface wind in knots (V_s). Kraft (1961) was the first to modify Fletcher's equation to account for this. He used a slightly different value for the Atlantic environmental pressure to get

$$V_s = 14\ (1013 - p_c)^{0.5} \quad . \tag{4}$$

This equation is used now in the Atlantic area.

With the increase of reconnaissance flights at 70 kPa, an extrapolation technique was developed to estimate the central sea level pressure of tropical cyclones from 70 kPa data (Jordan, 1957). Modifications were made to compute maximum winds based upon minimum 70 kPa heights alone. These equations were used throughout the entire 1960's and most of the 1970's.

Atkinson and Holliday (1977) were the first to examine surface wind reports from exposed coastal or island stations where there was a high probability that the station actually experienced the maximum winds of the storm. They developed an empirical relationship that resembled the cyclostrophic equation, yet also represented the best nonlinear fit to the data. Their equation may be written as

$$V_{ah} = 6.7\ (1010 - p_c)^{0.6444} \quad . \tag{5}$$

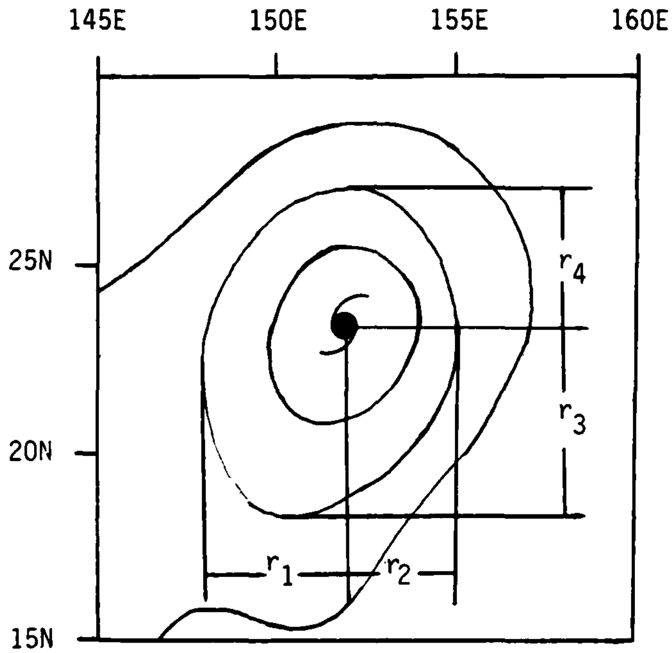
Even though (5) has proven to be a very good equation when applied to typhoons of the western North Pacific, there are some unanswered problems. Exact sustained one-minute-average wind speeds are very difficult to obtain from wind recorder data because of the rapid variation of wind speed during high speed conditions. Peak gusts were used and adjusted to sustained wind speed values using adjustment factors developed by the Air Force Cambridge Research Laboratory (Sissenwine et al., 1973). However, these adjustment factors were not developed for tropical cyclone wind and turbulence cases. In addition, (5) is the representation of the nonlinear regression line which best fits the data and, therefore, represents a mean of the data. Observations above the regression line, including those from sensors that broke or blew away at or before the maximum winds were recorded, are indicative of higher winds due to local pressure gradient or supergradient relationships.

Analytic models were developed by Depperman (1947), Schloemer (1954), and Holland (1980) to reproduce the horizontal profiles of tropical cyclone pressure and wind. The models contain parameters which are estimated empirically from climatological composites or from observations of specific storms. From these parameters, a geometric relationship is derived for winds both inside and outside the radius of maximum wind. Although analytic models are useful in approximating the general wind profile of the average hurricane/typhoon, the wind and pressure profiles of tropical cyclones vary considerably (Gray, 1981).

As mentioned earlier, a tropical cyclone can be analyzed in three ways (Merrill, 1982). The "intensity" is defined as the maximum sustained wind speed of the storm, and even though it can realistically be approximated for stronger storms from minimum sea level pressure alone, the location and extent of this maximum wind band can only be evaluated with sufficient data. Storm "strength" is defined as the average wind speed observed within the radial limits of the storm, and storm "size" is defined as a measurement of this radius. Little attention has been given to these latter two aspects. In addition, most research and modeling efforts have been concentrated on tropical cyclones which have attained hurricane/typhoon strength of 33 m s^{-1}. Comparatively little is known about the highly variable tropical depression and tropical storm structure, even though most tropical cyclones either never attain hurricane/typhoon strength or remain at "depression" or "storm" intensity for a significant portion of their life cycle.

The strength of a storm varies considerably with time. The strength is considered to be dependent on the overall average wind speed within the cyclone, not just the maximum wind. To demonstrate this variability, we can compare the strengths of two super typhoons (Judy and Tip) of the western North Pacific in 1979. Super typhoons are a subset of typhoons in which the maximum surface winds reach or exceed 67 m s^{-1} at some time during the life of the storm. Aircraft reconnaissance data collected on these two storms indicated that Judy had a much more compact pressure and wind distribution than Tip. This comparison can only be estimated qualitatively, since adequate quantitative data during the periods of maximum intensity of these two storms could not be obtained at close range due to the storm's remote location, size, and avoidance by all but reconnaissance aircraft. From analysis of the reconnaissance data, however, it appears that Judy had an extremely compact, maximum wind band with all the significant winds within a very small radius, thus affecting only a small area, though the maximum wind speed was higher for Judy than for Tip. However, Tip had a very broad band of significant winds, which affected a very large area for a considerable period of time. Although minimum sea level pressure and maximum surface winds have a statistical correlation, the wind field depends on the pressure gradient, not the minimum pressure itself. An objective method to depict accurately the pressure gradient and wind profile of a tropical cyclone would be of great help to forecasters, especially in sparse data regions.

In addition to strength, the effects of the cyclone's size are considerable. This is true even for the range of sizes that has been observed for tropical cyclones in the same intensity category. Super Typhoon Judy attained a minimum sea level pressure of 88.7 kPa and had a diameter (d) of no greater than 1150 km, as determined by analysis of its outermost closed surface isobar. The method of computing the average radius of the outermost closed isobar (AROCI) is shown in Fig. 1. According to Dunnavan and Diercks (1980), Super Typhoon Tip reached a record minimum sea level pressure of 87 kPa (only slightly lower than that of Judy) and had a record diameter of nearly 2220 km, about twice the corresponding value for Judy. Even though a more extreme example of size difference could be cited by using Hurricane Tracy of Australia instead of Typhoon Judy, the comparison of Judy and Tip (the same year and general location) shows the vast difference in size of certain storms with nearly the same minimum pressure and estimated intensity. The area affected by cyclonic winds ($0.25\pi d^2$) was nearly four times greater for



AROCI = $(r_1+r_2+r_3+r_4)/4$

Fig. 1. Method of computing the average radius of the outermost closed isobar (AROCI). On most maps the isobars are at a 4 mb interval.

Tip than for Judy.

Bates (1977) developed a normalized profile of vertical wind speed variation for the standard tropical cyclone. This profile provides a theoretical relationship between the winds at the 70 kPa level and those at the surface. Consequently, comparisons of winds at a 70 kPa flight level with those at the surface would be expected to yield fairly consistent results. Whenever surface wind speed estimates are in excess or well below these expectations, the estimates are usually disregarded. However, not only may the measured flight level winds be in error, but the normalized wind profile is meaningful only in the event that the storm is symmetric and vertically aligned. Huntley and Diercks (1981) found that, in 1979, 47% of the western North Pacific typhoons exhibited a significant vertical tilt between their surface and 70 kPa centers. The concept of a tilted vortex has been used in the two-layer discrete vortex model of Khandekar and Rao (1971) to study the short-term displacements of tropical vorticies due to mutual interaction. During the developing stage of a tropical cyclone, separation between 70 kPa and surface centers has been observed to be over 100 km and on rare occasions over 200 km. In the later stages, the tropical cyclone often tilts with height significantly in the direction (downstream) of strong upper level steering flow. During these periods, surface and upper level winds may differ considerably.

Recent studies conducted at Colorado State University by Weatherford and Gray (1984), Weatherford (1985), Merrill (1985), and Edson (1985) indicate that changes in tropical cyclone intensity are not correlated well with changes in the outer wind strength (or that wind between about 100 to 280 km from the center). A somewhat better correlation exists when both eye size and minimum pressure are known, but eye size cannot always be determined. For this reason, as well as the other factors previously discussed, other methods of data analysis are desirable.

CHAPTER IV

DATA DESCRIPTION

The 54th Weather Reconnaissance Squadron of the United States Air Force is the primary aircraft reconnaissance unit to gather information from the numerous tropical cyclones of the western North Pacific. In an average year, approximately 30 tropical cyclones develop within the western North Pacific basin. The author participated in reconnaissance flights in this area during the period 1979-1981.

Over one full year of reconnaissance data was used in this study. The 1980 year group was chosen because of the rather random assortment of storms which developed during that year and the author's experience and knowledge of them. Additionally, the data from Super Typhoon Tip (1979) were included because of the unique characteristics of this typhoon.

Tropical cyclone reconnaissance missions are flown basically at two specific levels. Low level investigative flights are made during the formative stages of the system when winds are below 25 m s^{-1}. These flights are flown at altitudes of between 150 and 500 m above the ocean, and sea level pressures are extrapolated from flight level D-value information. Once the storm has definitely developed into a closed circulation, flights are conducted at the 70 kPa level along radial legs both into and out of the center.

Data collection frequency also varies between low level and 70 kPa level missions. For the low level missions, the data of interest for this study were collected approximately every 15 minutes or 85 km.

These data included the date/time group, latitude and longitude of the observation, flight level wind, sea level pressure, and surface wind. The data collection frequency for 70 kPa missions was basically every 55 km within 280 km of the center. The data of interest at this level are the date/time group, latitude, longitude, flight level wind, height of the 70 kPa surface, and the surface wind (if observable).

The initial flight path at low level is flown toward the forecasted center position (Fig. 2). Usually these missions are flown before a definite surface circulation has been observed. The forecasted position usually is estimated from a satellite image of the area of disturbed weather and usually is inaccurate because of the lack of cloud definition at this stage of development. Even when a circulation pattern is indicated, the circulation may be at middle levels and may not be evidenced at the surface. When the forecasted position has been reached by the aircraft, a counterclockwise pattern is flown to close off the circulation (if any).

The 70 kPa missions are flown in triangular crossing patterns (Fig. 3). Along the incoming radial leg, an observation is taken at 465 km, 280 km, and then every 55 km until the center is fixed. An exit leg is flown out, in the same manner, to 280 km, and a base leg is flown with observations taken about every 130 km. These patterns are repeated for two or three fixes of the storm's center. The track between fixes requires about three hours to complete.

The procedures used in obtaining, sorting and processing the aircraft reconnaissance data are contained in the Appendix. The Appendix includes information on the source of raw data, the format in which the

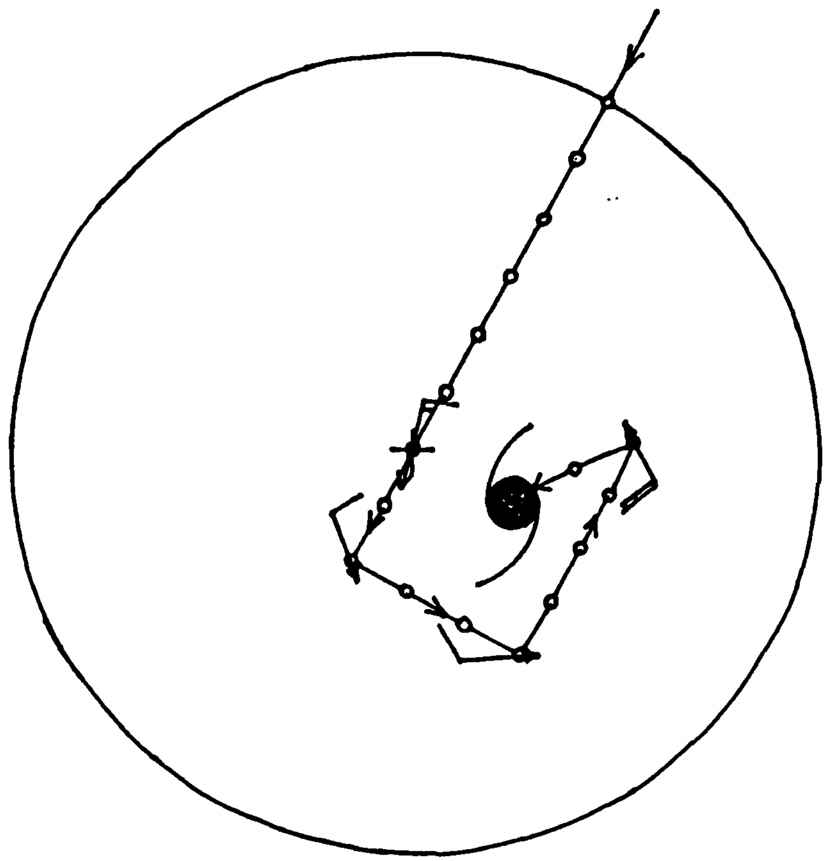


Fig. 2. Flight path of a typical low level investigative mission. Observations are taken at each circled point.

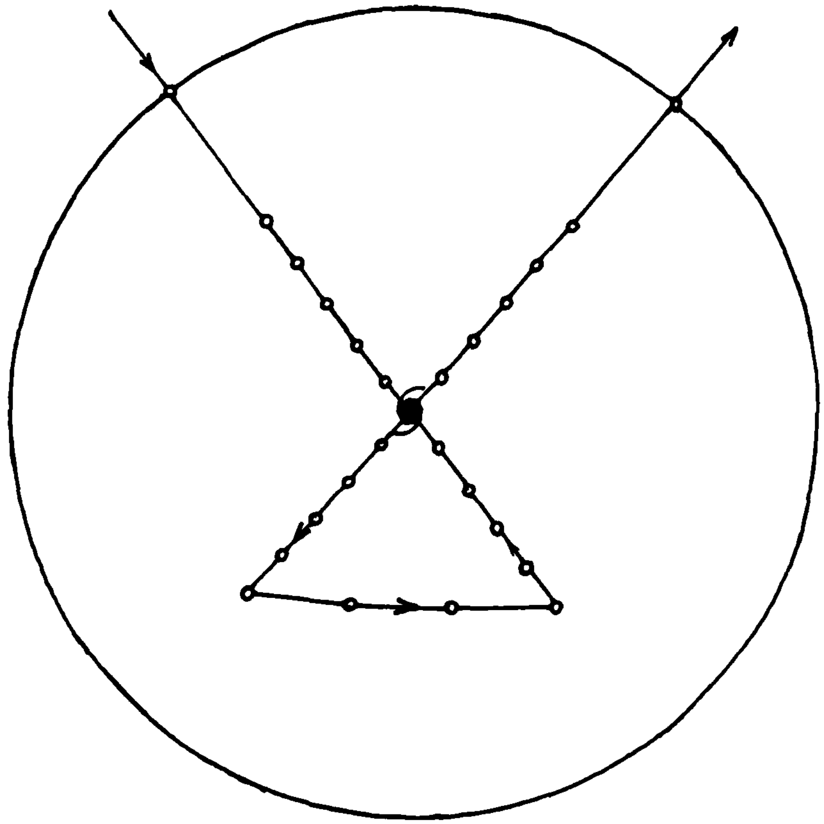


Fig. 3. Flight path of a typical 70 kPa fix mission. Observations are taken at each circled point (about 55 km apart).

data are ordered for computation, the derivation of the equations used with the data, the computer program employed, and detailed annotations to the computer program.

The next chapter presents and discusses the results of the computations.

CHAPTER V

RESULTS

In the following discussion, a synopsis will be given of the computer output and its statistical significance. The applications of this result will be interpreted in terms of intensity and strength. Finally, the reliability of the size measurement capability will be summarized.

The output of the computer program for each set of observations with pressure data was composed of ratios of the observed (average or maximum) wind speed to the corresponding surface pressure gradient or 70 kPa height gradient between observations. Units of the output were in n mi^2 h^{-1} mb^{-1} or n mi^2 h^{-1} f^{-1}, and they were left that way for simplicity since the input data were in these terms. The values themselves were not as important as their repeatability, so that for a given height or pressure gradient a realistic value of wind could be assumed even if winds were not directly observable at the time (i.e., nighttime or inoperative wind sensors). The ratios were manipulated statistically to define mean relationships between wind and pressure/height gradients, the normalcy of their distribution, and their standard deviation (or variance). It was hoped that the final results would have a normal distribution, a small variance, and that they would support the use of empirical relationships to obtain approximate wind speeds from observed pressure/height gradients alone. The various correlations defined in the Appendix were all determined simultaneously to ascertain if some of the correlations were more reliable than others.

The output values were divided into groups which were dependent on the radial distance from the vortex center. Since data were gathered approximately every 55 km from the center, this distance increment was used as the basis for the grouping. In doing so, the effect of radial distance was adjusted in a rough manner in the results. If the midpoint between two observations with pressure data lay within 55 km of the center, the resultant pressure/wind relationship was placed in group 1. If the midpoint was between 56 and 110 km from the center, the result was placed in group 2, etc. The output data also were grouped into four intensity categories, using the central pressure thresholds that correlate to the transition point in (5) from depression to tropical storm, tropical storm to typhoon, and typhoon to super typhoon. This was done to isolate those characteristics common to weaker storms from those common to stronger storms.

A statistical analysis was completed to evaluate the distribution of the output. Figure 4 compares the distributions of the ratios of maximum surface wind/sea level pressure gradient within 55 km of the center for the four storm intensity categories (depression, tropical storm, typhoon, and super typhoon). The stem and leaf plots of Fig. 4 approximate histograms of the output values for the above named distribution (Koopmans, 1981). The box plots show how the distribution compares to a normal distribution. Significant outliers and positive skewness indicate that the results are not a normal distribution. This is verified also by the large differences between mean and median values.

Table 1 compares the mean and median values of the distributions (similar to those of Fig. 4) for the ratio of average surface wind to sea level pressure gradient and the ratio of maximum surface wind to sea level pressure gradient. As an example, the mean and median values for

```
STEM LEAF
  16 1                                          #      BOXPLOT
  14                                            1         *
  12
  10
   8 77
   6 0                                          2         *
   4 01344619                                   1         |
   2 001222333567777892223479                   8         |
   0 23566788900111333444666677778889          24      +--+--+
  -0                                           31      *-----*
  -2
  -4
  -6
  -8 5
 -10 1                                          1         *
     ----+----+----+----+----+----+-            1         *
     MULTIPLY STEM.LEAF BY 10**+02
```

(a)

```
STEM LEAF
   7 7                                 #      BOXPLOT
   7                                   1         *
   6
   6 3
   5                                   1         *
   5
   4 6
   4 024                               1         0
   3 6779                              3         0
   3 012                               4         |
   2 5566788899                        3         |
   2 000001111122234                  10         |
   1 555555666777788899999            15      +-----+
   1 0000111112222222333344444        21      *--+--*
   0 556677888889999                  24      +-----+
   0 234                              15         |
     ----+----+----+----+----          3         |
     MULTIPLY STEM.LEAF BY 10**+02
```

(b)

Fig. 4. Stem and leaf plots and box plots for the maximum surface wind/sea level pressure gradient computations within 55 km of the center for (a) depressions, (b) tropical storms, (c) typhoons, and (d) super typhoons. The mild and extreme outliers of the distribution are signified by 0 and *, respectively, on the box plot. Units in n mi^2 h^{-1} mb^{-1}. (See text).

```
    STEM LEAF                                #          BOXPLOT
      30 64                                  2             *
      28
      26 1                                   1             0
      24
      22 2457                                4             0
      20 08                                  2             0
      18 479                                 3             |
      16 111                                 3             |
      14 234578                              6             |
      12 026661345                           9             |
      10 0013334566771345678999             22          +-----+
       8 122334577891244556679999           24          *--+--*
       6 112234445578001233344456           24          +-----+
       4 0000037011111225578999             22             |
       2 2344589                             7             |
         ----+----+----+----+----
(c)      MULTIPLY STEM.LEAF BY 10**+01
```

```
    STEM LEAF                    #          BOXPLOT
       8 4                       1             *
       7
       6
       5
       4 237                     3          +-----+
       3 13444599                8          *--+--*
       2 46                      2             |
         ----+----+----+----+
(d)      MULTIPLY STEM.LEAF BY 10**+01
```

Fig. 4. (Continued).

Table 1. Comparison of the mean ($\overline{X}$) and median (M) values for wind/pressure relationships categorized by intensity of and distance from the vortex center. The relationships are average surface wind/sea level pressure gradient (ASW/SLPG) and maximum surface wind/sea level pressure gradient (MSW/SLPG). Units are n mi^2 h^{-1} mb^{-1}.

Intensity	Distance (km)	ASW/SLPG		MSW/SLPG	
		$\overline{X}$	M	$\overline{X}$	M
	0 - 55	223	178	237	200
	56 - 110	371	336	452	407
Depression	111 - 165	612	561	741	640
	166 - 220	436	493	502	523
	221 - 280	577	584	651	651
	0 - 55	177	153	190	165
	56 - 110	333	281	383	299
Tropical Storm	111 - 165	504	419	548	452
	166 - 220	470	404	536	456
	221 - 280	653	546	743	603
	0 - 55	94	83	100	91
	56 - 110	238	185	254	198
Typhoon	111 - 165	382	314	418	341
	166 - 220	518	425	555	448
	221 - 280	500	416	311	416
	0 - 55	37	34	39	35
	56 - 110	218	195	242	198
Super Typhoon	111 - 165	283	256	293	275
	166 - 220	534	411	558	448
	221 - 280	706	567	546	628

the 0-55 km distance range in Table 1 correspond to the mean and median values of the stem and leaf plot in Fig. 4a. Thus, the mean ratio of the average surface wind (ASW) to the sea level pressure gradient (SLPG) is 223, whereas the median ratio value is 178. The other correlations that were tabulated by the computer (i.e., 70 kPa wind/70 kPa height gradient and surface wind/70 kPa height gradient, etc.) exhibited similar tendencies and are not shown. The effects of the mild or extreme outliers skew the means considerably, widen the difference between mean and median, destroy distribution normalcy, and limit the data's usefulness in determining empirical relationships.

Figure 4a indicates the presence of significant negative outliers. These are generally a result of inaccurate pressure gradient computations, incorrect wind measurements (or estimates), or strong local wind effects. Pressure gradient inaccuracies can be attributed to the effects of rounding error, poor navigational positioning, pressure measurement error, or possibly even an invalid sea level pressure extrapolation assumption. Local wind effects, such as a thunderstorm outflow, also may be contrary to the assumed wind of the observed pressure/height gradient. The negative relationship commonly occurs in weak pressure gradient situations (0.1 - 0.2 kPa differences between observations), in broad light and variable wind areas, or where the flight path is nearly parallel to the height contours or isobars of the pressure field. The same inaccuracies also may account for some of the positive outliers. More restrictive requirements covering the normalcy of the flight path to the pressure field may be necessary to prevent these data from affecting the results. The wind measurement itself is another factor in the variability of the outcome. The ability to determine correctly the average or maximum wind speeds is subject to question when only two or three wind measurements are taken along a 55 km track. Added to this are the factors of Doppler radar attenuation in heavy precipitation and unobservable surface winds during undercast cloud conditions.

A. Intensity

The gradient winds were computed using the equation,

$$V_{gr} = \frac{-fr}{2} + \left[\left(\frac{fr}{2}\right)^2 + \frac{rR_d T_v dp}{pdr}\right]^{0.5} , \tag{6}$$

where V_{gr} is the gradient wind, f is the Coriolis term, r is the radial distance from the vortex center to the midpoint between observations, R_d the specific gas constant, T_v is the virtual temperature (assumed to be a constant 29°C), dp the change in pressure between observations, p is the assumed pressure at the midpoint, and dr the distance between observations along the same radial line. For small values of r (less than 55 km) at low latitudes, the $\frac{fr}{2}$ term is negligible such that

$$V_{gr} = V_c = \left(\frac{rR_d T_v dp}{pdr}\right)^{0.5} , \tag{7}$$

where V_c is the cyclostrophic wind.

Tables 2-5 contain comparison summaries of randomly selected storms in all four intensity categories. The tables compare the computations of surface winds from the computer program (V_{cbs}), the maximum wind

Table 2. Comparison of the computed and observed maximum surface winds within 55 km of the center of a tropical depression. Units are in m s^{-1}.

Winds as computed by different methods			Observed maximum surface wind
V_{cbs}	V_{ah}	V_{gr}	
19	13	13	13
11	12	11	9
3	5	7	4
5	8	9	10
24	16	13	11
38	16	15	15
17	13	9	30
5	8	7	12
24	8	9	3
24	14	16	8
12	16	15	15
18	16	15	10
16	16	15	22
19	16	16	11
16	16	17	19
13	16	15	15
4	10	7	6
6	12	9	10
30	14	13	23
10	14	9	6
10	14	11	22
4	11	7	28
27	14	17	23
44	14	19	15
9	13	13	16
7	7	7	5
17	16	17	21
29	16	19	20

Table 3. As Table 2, except for tropical storms.

Winds as computed by different methods			Observed maximum surface wind
V_{cbs}	V_{ah}	V_{gr}	
28	25	23	33
22	22	20	26
30	23	19	25
12	17	16	9
13	17	16	23
17	17	16	15
26	23	20	24
36	23	20	24
22	22	21	29
33	22	22	22
36	23	22	21
29	23	20	25
36	33	26	11
52	33	27	24
28	20	19	17
24	20	19	5
40	29	24	28
40	29	25	24
29	29	18	22
28	20	19	16
46	31	24	42
53	31	31	39
8	25	9	20
10	25	11	6
16	21	16	16
13	21	13	28
24	22	17	20
12	22	17	23
22	23	17	24
29	23	20	22
29	22	23	29
28	27	22	12
31	23	25	32

Table 4. As Table 2, except for typhoons.

Winds as computed by different methods			Observed maximum surface wind
V_{cbs}	V_{ah}	V_{gr}	
30	38	35	28
25	38	33	29
33	52	32	45
46	52	35	48
33	34	24	30
46	34	32	23
63	54	32	44
43	54	37	42
28	38	25	43
46	38	33	43
98	60	53	52
62	60	47	47
28	44	32	43
51	42	30	23
41	44	39	38
38	44	38	41
101	64	54	59
154	64	57	51
27	36	27	32
44	41	41	38
29	41	28	31
40	41	33	36
63	48	43	54
72	48	43	52
67	50	39	57
62	50	45	53
10	34	19	13
9	34	16	17
36	34	31	35
20	43	25	24
29	37	30	34
44	37	31	33
69	49	44	44

Table 5. As Table 2, except for super typhoons.

Winds as computed by different means			Observed maximum surface wind
V_{cbs}	V_{ah}	V_{gr}	
59	71	59	63
72	71	60	66
61	75	63	67
74	75	64	66
85	83	66	69
61	83	67	63
114	82	61	74
77	82	63	67
55	79	64	69
101	73	61	62
71	73	67	64
80	75	69	68
73	75	68	71

based on the Atkinson and Holliday equation (V_{ah}), the gradient wind (V_{gr}), and the observed maximum surface wind. We must assume that the maximum winds will be found within 55 km of the center, although this may not be the case for depressions and other disorganized storms. In comparing the three methods, the variability of using the data empirically (V_{cbs}) is evident, especially for typhoons and super typhoons (Tables 4 and 5), and it is more realistic to assume that the gradient wind and the Atkinson and Holliday methods are better.

Figure 5 is a plot of the average differences between V_{ah} and V_{gr} for the four intensity categories. As the storm intensifies, V_{gr} increasingly underestimates the maximum wind (if we assume V_{ah} to be correct). This can be explained by the classic pressure configuration within the eyes of tropical cyclones. Even without an organized eye wall, the pressure profile cannot be approximated by the gradient wind relationship once inside the maximum wind band. Many theoretical wind approximations of the tropical cyclone have assumed solid rotation within the radius of maximum wind. In other words, the winds are expected to decrease to zero in a linear fashion from the point of maximum wind to an infinitely small calm center. In reality, this is not the case. Most storms show a broad minimum pressure center with light and variable or calm winds. These minimum pressure centers commonly have radii of 10-20 km. In Fig. 6, the actual minimum pressure center of radius r_p is characterized by virtually no pressure gradient or measurable wind. It is, therefore, useless to include this distance in the innermost estimation of V_{gr}. If, however, r_p were used to adjust the distance over which the pressure gradient is measured (change r_o to r_o') and to adjust

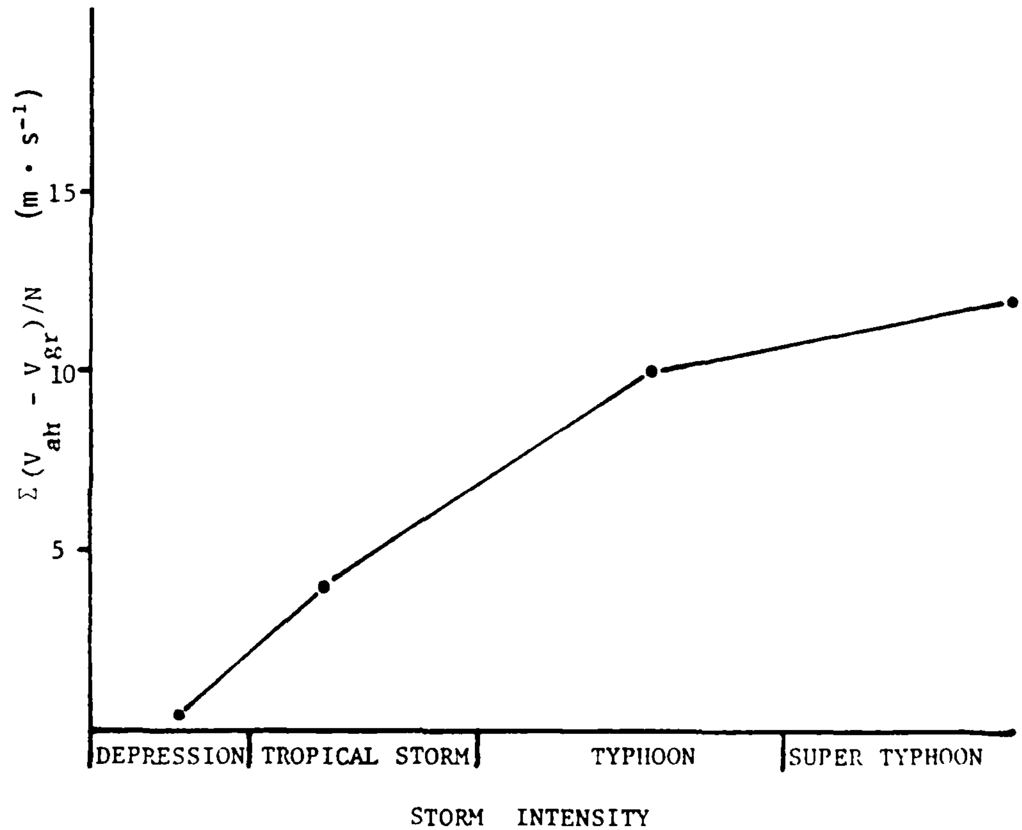


Fig. 5. Average differences between V_{ah} and V_{gr} for the four tropical cyclone intensity categories.

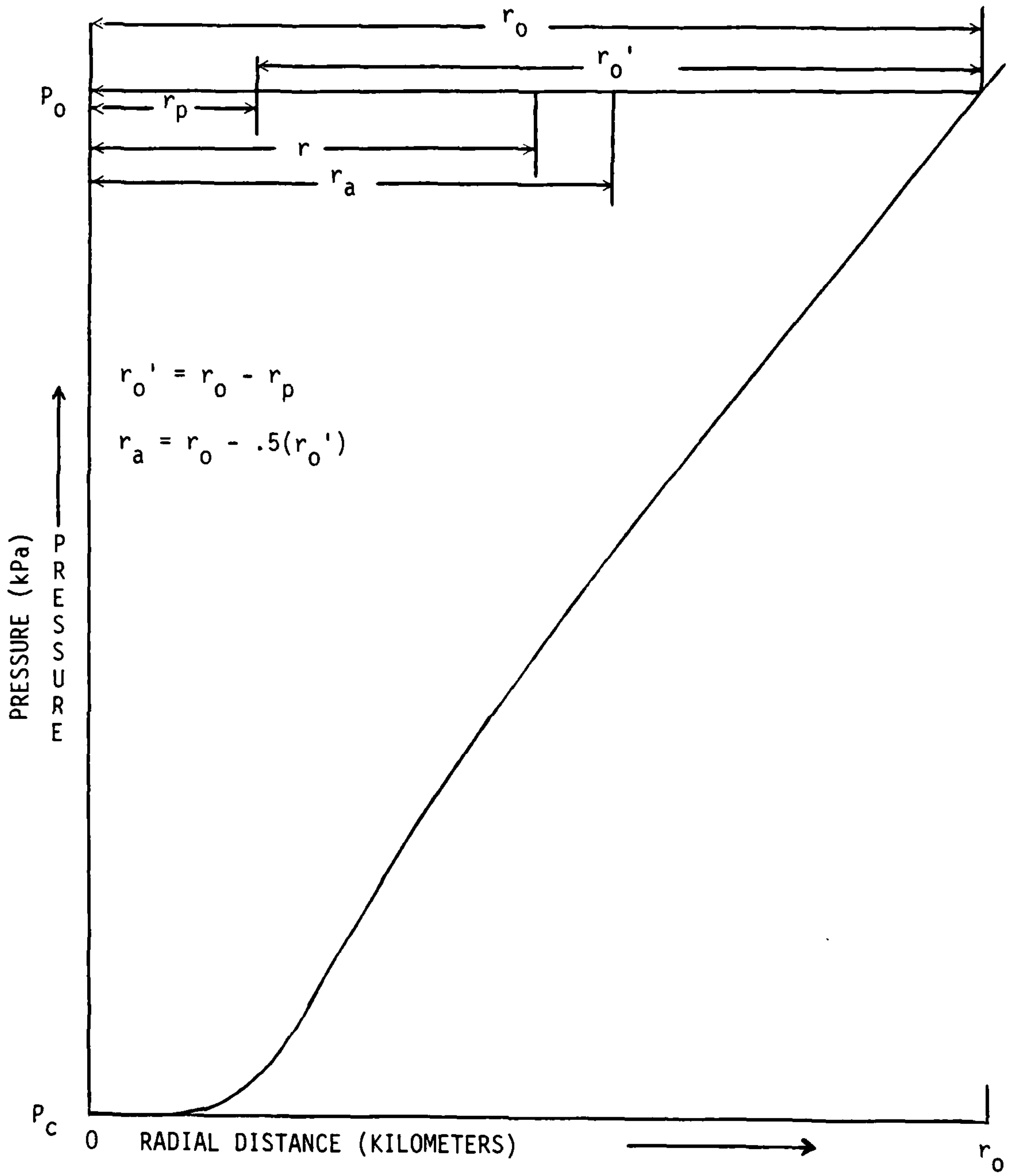


Fig. 6. Adjustment of the distance over which pressure gradient is measured (r_o to r_o') and the radius of measurement (r to r_a). The minimum sea level pressure radius (r_p) represents the point on the pressure curve after which a quasi-linear approximation can be made.

the radial distance to the midpoint for which this gradient applies (change r to r_a), then by substituting r_a for r and r_o' for dr in (7), the differences between V_{ah} and V_{gr} would be approximately offset. As an example, a super typhoon at 15° latitude with minimum sea level pressure of 89 kPa and a radial distance of 55 km (r_o) to an observation with a pressure rise (from the central pressure) of 8.6 kPa (dp = 8.6 kPa) would require a minimum pressure center radius (r_p) of 9 km to offset the 12 m s^{-1} difference between V_{ah} and the original V_{gr}. This is a realistic value for storms of this intensity.

Figure 7 shows that not only is $\Sigma(V_{ah} - V_{gr}) / N > 0$ for typhoons and super typhoons, but the same relation holds true for the average differences between V_{ah} and the maximum surface winds observed (estimated) by aircraft observers (V_o). Although $\Sigma(V_{ah} - V_{gr}) / N$ and $\Sigma(V_{ah} - V_o) / N$ exhibit similar trends, the degree to which V_o is less than V_{ah} is accounted for in a different way. During the depression stage, there is generally less cloudiness below observational altitude that will interfere with the observation of the maximum surface wind. Additionally, flights are frequently flown at low levels during the depression stage, which allows for more accurate wind estimations. As storm strength increases and an eye wall forms, the chances increase that the maximum winds will be missed while the aircraft is in heavy precipitation or the eye wall cloud. Estimations of surface winds above 67 m s^{-1} are further complicated by the inability to distinguish changes when the surface is obscured by spray. With the adjustment for system motion, five of the thirteen observed winds in Table 5 are above 67 m s^{-1}; however, only two of the original wind estimates (V_{gr}) were for

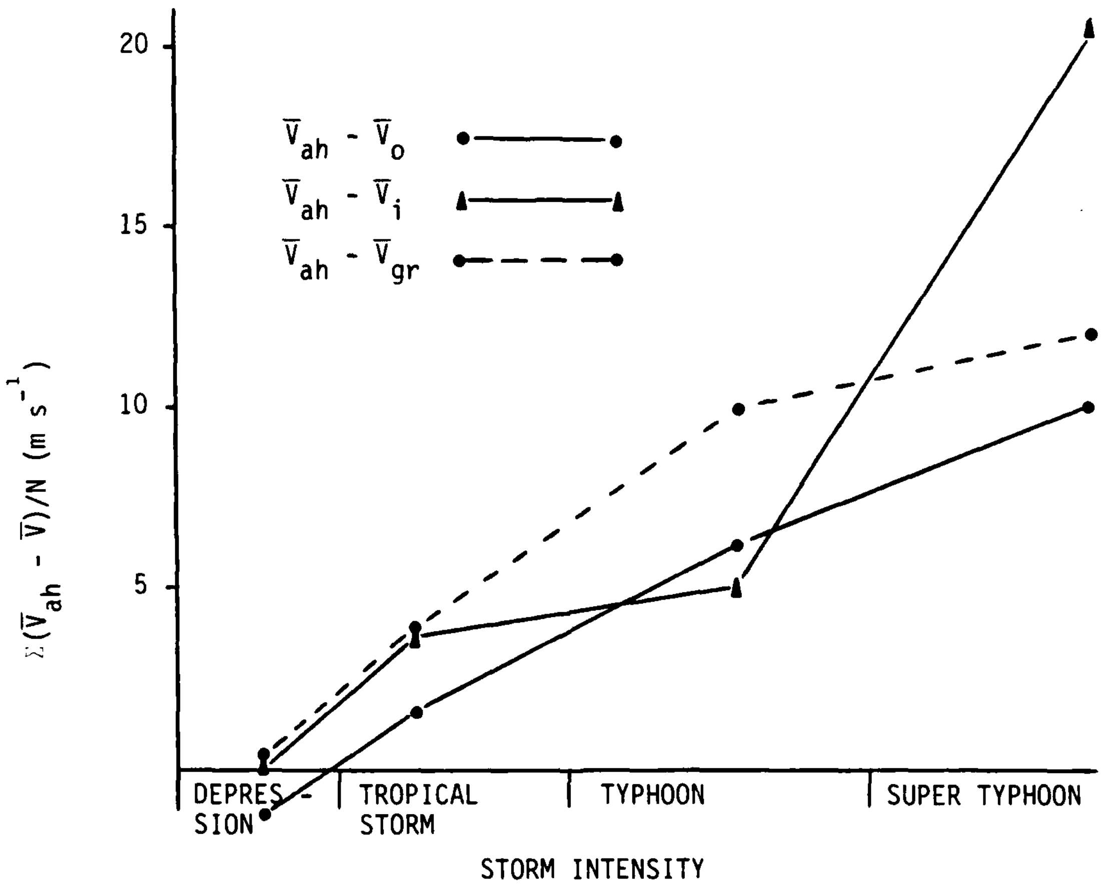


Fig. 7. As Fig. 5, except between V_{ah} and V_o, V_{ah} and V_i, as well as V_{ah} and V_{gr}.

winds in excess of 67 m s^{-1}.

Figure 7 also shows a similar comparison for instrumentally observed maximum winds at flight level (V_i). The same tendency occurs with increasing storm intensity as was the case for the observations of surface wind. This is due to the general increase in heavy precipitation with the more intense storms. Additionally, Doppler radar systems often reach their maximum drift angle measurement capability during penetration of the eye wall, preventing instrumental measurement of the maximum winds.

We must either assume that V_{ah} overestimates the maximum wind or consider both measured and estimated winds from aircraft as unreliable. The latter hypothesis is preferred in light of the high variability of the computed wind data of this study and the known problems of accurately observing winds from aircraft. However, with an accurate approximation of the radius of minimum pressure change (r_p) within tropical cyclone centers and accurate position reports, a meaningful intensity approximation is attainable from the aircraft pressure data.

B. Strength

Figures 8-11 are wind profiles of selected radial legs flown into or out of tropical cyclones of all four intensity categories. All winds in the figures have had the motion of the system subtracted. As would be expected for tropical depressions (Fig. 8), there is no classic wind or pressure relationship such as is common for much stronger storms. The profile for Tropical Storm Forest is for the period approximately 18 hours before he was classified as a tropical storm. The closest

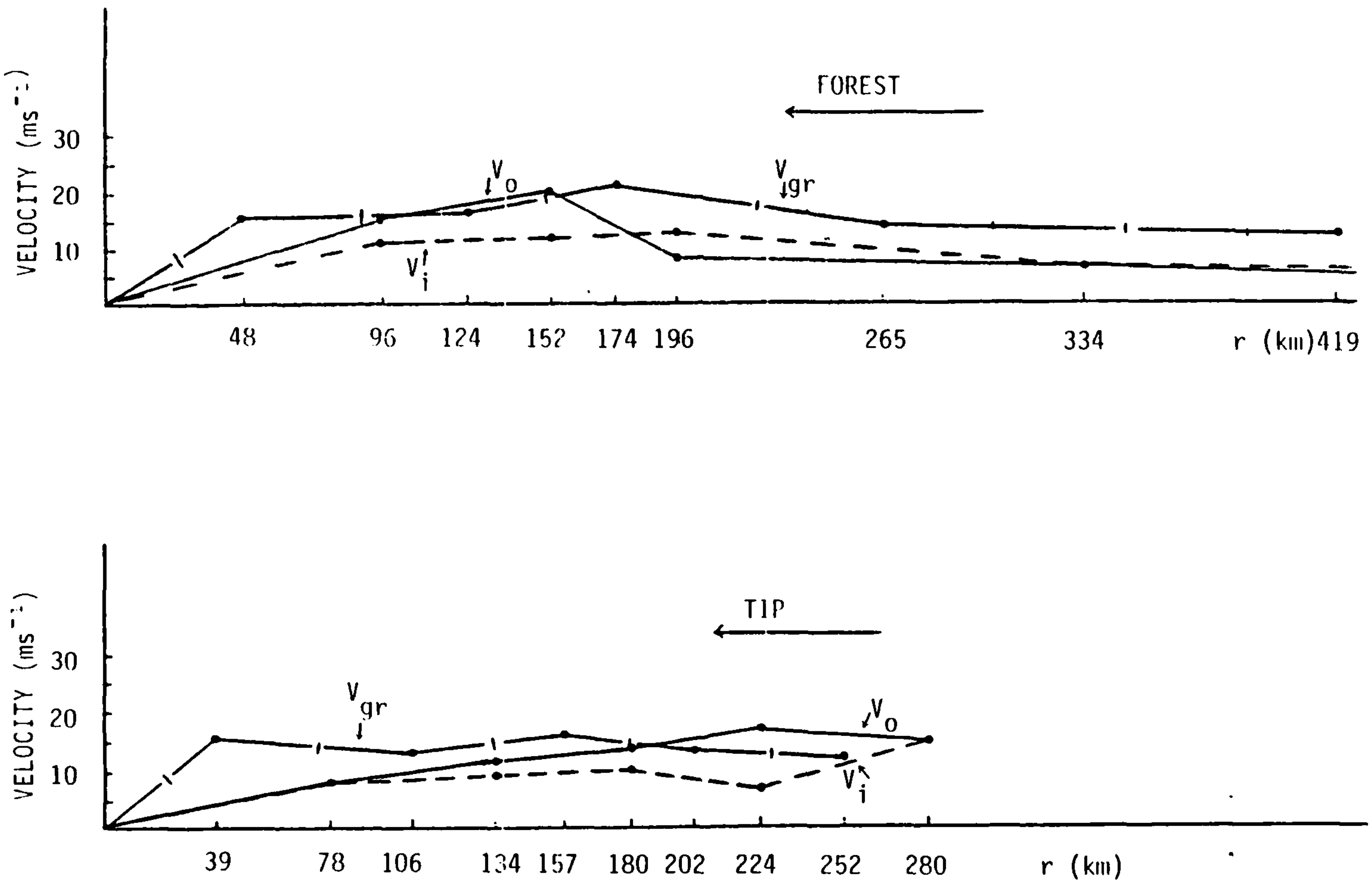


Fig. 8. Wind profiles in two tropical depression sectors. The profiles include traces for V_o (solid line), V_i (dashed line), and V_{gr} (segmented line). The arrows show direction of aircraft flight.

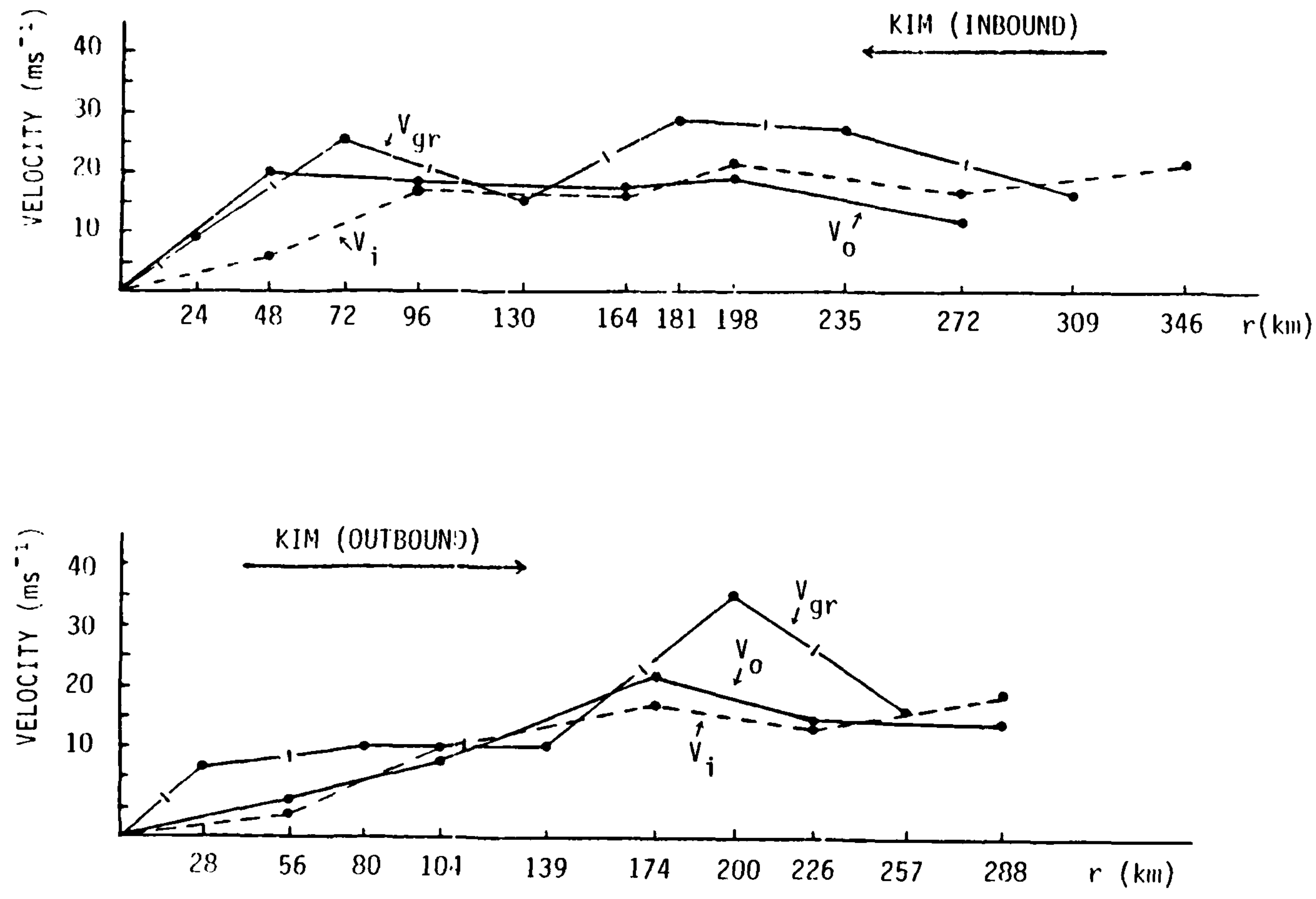


Fig. 9. As in Fig. 8, except for two sectors of Tropical Storm Kim.

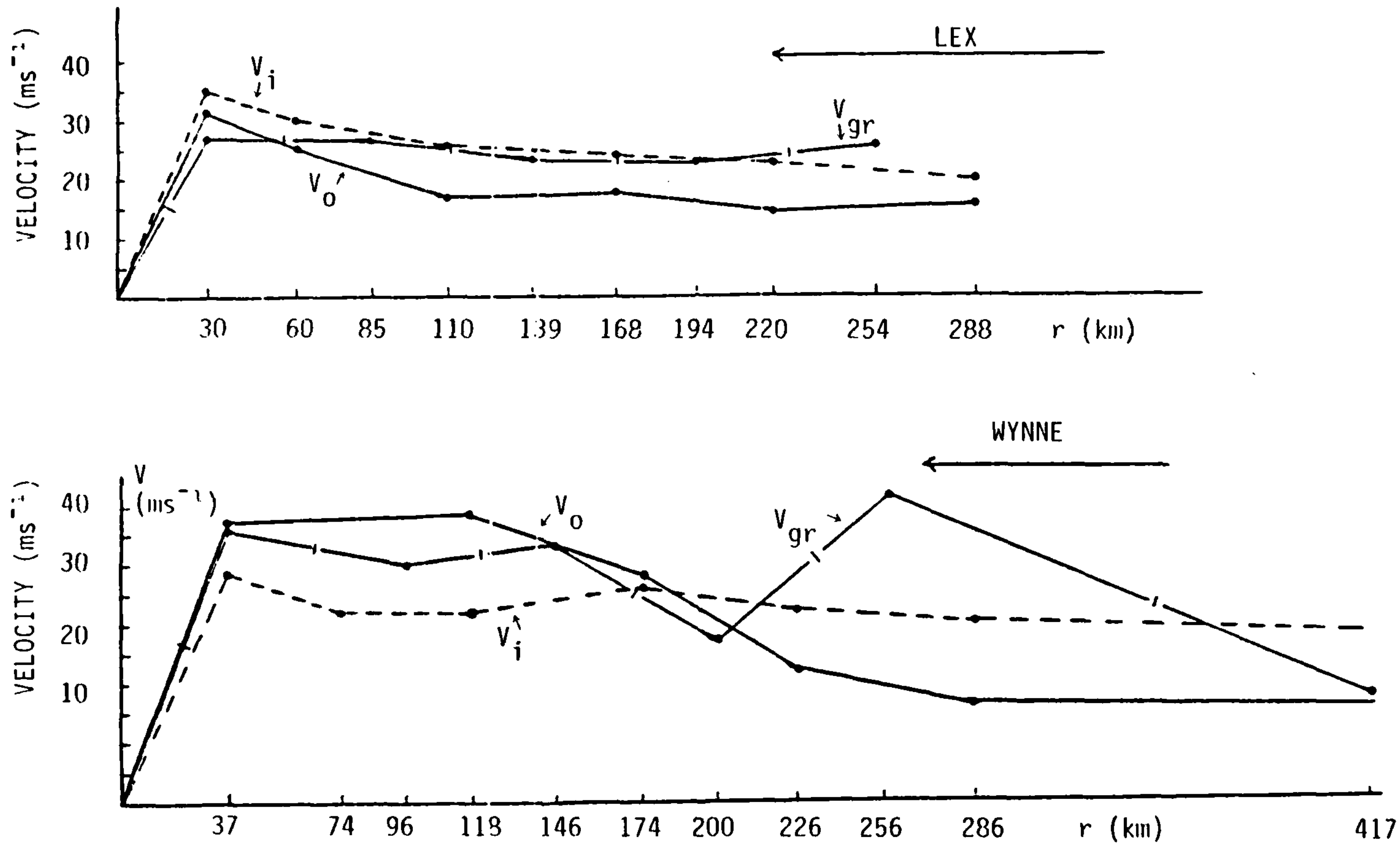


Fig. 10. As in Fig. 8, except for typhoons.

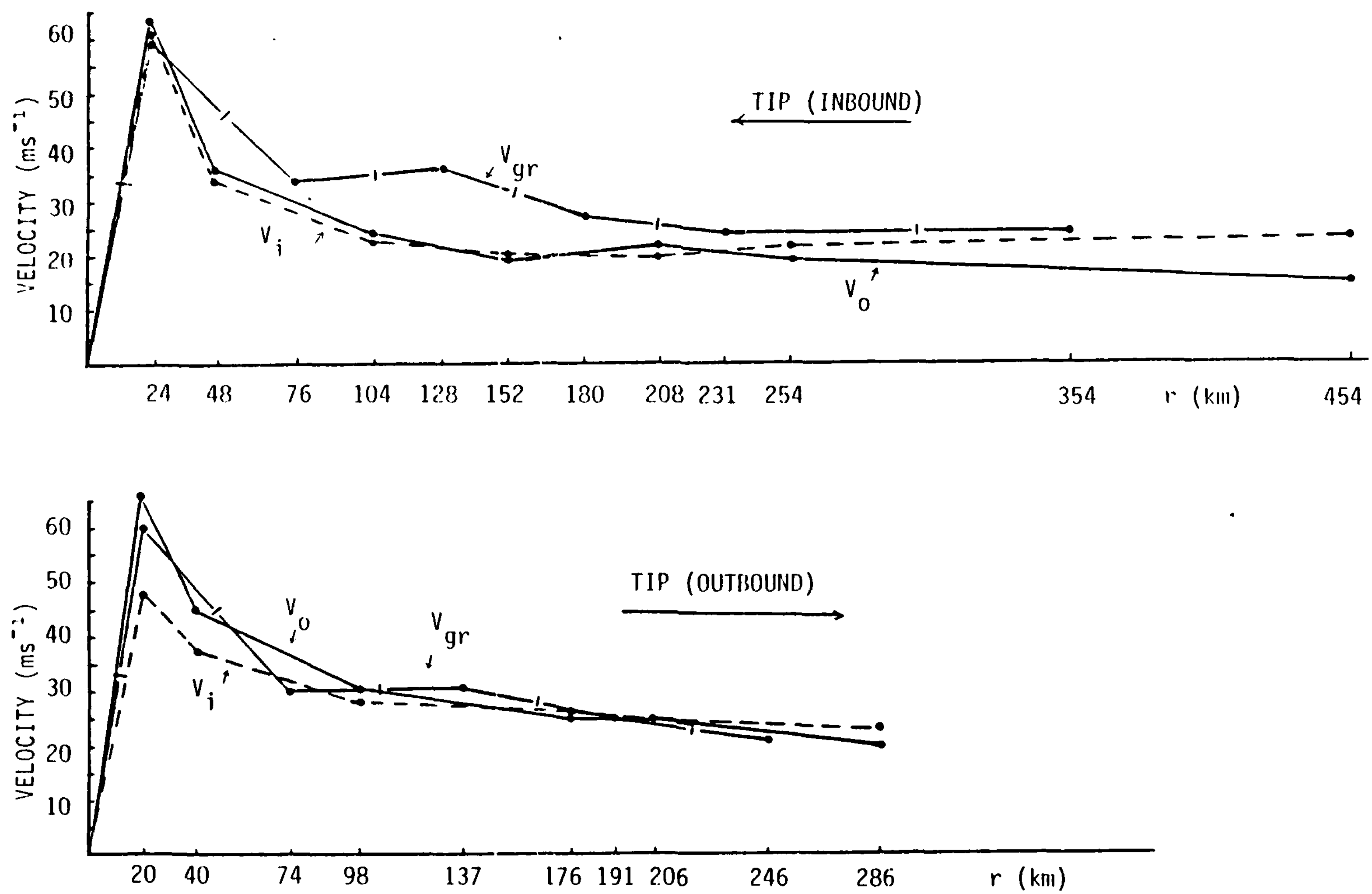


Fig. 11. As in Fig. 8, except for Super Typhoon Tip.

observation to the center indicated that there were surface winds of 15 m s^{-1} at 96 km from the center, but from that point on into the center there is no information. The pressure gradient information seems to support the observed wind, and a secondary maximum of V_{gr} at 174 km (21 m s^{-1}) would seem to justify the observed maximum surface winds of 20 m s^{-1} at 152 km. The minimum sea level pressure of 99.9 kPa would support a maximum wind of only 16 m s^{-1} using (5), and without knowing of the V_{gr} maximum outside 100 km there would be no reason to suspect the existence of stronger winds at that range. But successive tracks through the area observed the strongest winds between 100 and 130 km from the center.

The profile of what would become Typhoon Tip is also included in Fig. 8. The gradient wind would seem to indicate that winds of 10 m s^{-1} were justified outside of 80 km and would also seem to indicate that winds would pick back up again within 70 km of the storm. This was not to be the case. To help explain the reason for this, we must bring in the concept of vertical tilt of the storm. In order for V_{gr} to be computed in (6), the surface pressures were used to determine dp. However, the surface pressures themselves were extrapolated from 70 kPa heights, which are related to the 70 kPa center but not directly related to the surface center. Only when surface and 70 kPa centers are vertically aligned can we assume that extrapolated sea level pressure from 70 kPa data will duplicate actual sea level pressures at the surface. If the surface center is displaced in the horizontal from the 70 kPa center, the extrapolated sea level pressures will be unlikely to approximate the actual surface values and estimating dp becomes unreliable even though dr between the observation point and both centers is accurately determined. In this particular case, the vertical displacement of the storm was judged to be 70-80 km between sea level and 70 kPa (Huntley and Diercks, 1981). This complicated the accuracy of sea level pressure extrapolations and subsequent computations of V_{gr} close to the center.

The profile for Tropical Storm Kim is shown for successive tracks in two separate sectors (Fig. 9). Following the route of flight on the inbound track, it is interesting to note that a relatively strong wind zone exists at around 200 km. The value of V_{gr} computed at 235 km between the observations at 198 and 272 km indicates that winds should increase, although the observed winds do not increase as much as predicted. The V_{gr} computed for 181 km is significantly higher than the observed wind, which actually decreases by 164 km as compared with the value at 198 km. Considering that the navigational positioning error may be 11 km or more (positions are rounded to the nearest tenth of a degree in latitude and longitude), an adjustment to the observational position from 164 km to 153 km would decrease V_{gr} at 181 km by 4 m s^{-1}. This value of V_{gr} would still appear to overestimate the observed wind but would indicate that a slight decrease in wind speed (as observed) was likely. The increase in V_{gr} at 72 km is reflected in a slight increase in surface wind at 48 km without a corresponding increase in flight level winds. This may be due to vertical tilt effects since the inbound observations were taken from a position 4-5 km closer to the 70 kPa center than to the surface center. On the outbound leg, the observed maximum winds that occurred at 174 km appear justified by V_{gr} if we assume that the pressure gradient increase takes place right at the 174 km observation. If we adjust the 174 km position by 11 km to 163 km, the computed V_{gr} at 139 km goes to 16 m s^{-1} and V_{gr} at 200 km falls to 34 m s^{-1}. This would appear more reasonable, but the tendency of V_{gr} to overestimate observed wind values remains.

The more classic profile appears for typhoons (Fig. 10). The inbound track on Typhoon Lex shows that V_{gr} does a fair job of approximating flight level winds but continues to exceed the estimates of surface wind. The inbound plot on Typhoon Wynne portrays a very strong storm. Typhoon force winds appear to extend to nearly 200 km. As this storm moves closer to a strong subtropical ridge over the Asian continent and North Pacific, a strengthened gradient extends outward to the north of the storm, and the storm seems to strengthen even though it is now past the super typhoon stage. The computation of V_{gr} above 50 m s^{-1} at 256 km does not appear to be justified and may be associated with an observational error.

Figure 11 is the plot of wind speeds along consecutive inbound and outbound tracks for Super Typhoon Tip. The observed winds on the inbound track appear to support that V_{gr} is too high. For example, the values of V_{gr} at 76, 128, 180, 231, and 354 km are all above the traces which connect the observed surface winds (V_o) and instrumentally sensed flight level winds (V_i). In fact, this would tend to indicate that for the five computations of V_{gr} outside of 70 km, V_{gr} was greater than V_o by around 7 m s^{-1} and V_i by over 6.5 m s^{-1}. However, the outbound track shows only slight differences between V_{gr}, V_o, and V_i. Even though maximum observed and instrumentally sensed winds are used in the figures, these winds may be underestimates of the true maximum wind values between observations. It was discussed that there are difficulties in observing or sensing maximum winds with the limited opportunities afforded by extensive cloud cover (which limits the view of the sea surface) and heavy rainfall (which attenuates Doppler speed measurements). Super Typhoon Tip had both of these traits, and it is quite likely that one quadrant of the storm (inbound track) was not conducive to measuring maximum values while another quadrant was conducive (outbound track). Given that there is a good correlation between V_{gr}, V_o, and V_i on the outbound track and since V_{gr} certainly does not underestimate maximum values of V_o and V_i, it can be assumed that V_{gr} is a good indicator when used to determine storm strength.

A comparison of the "strength" of Super Typhoons Tip (with p_c = 90 kPa) and Wynne (with p_c = 89 kPa) is made in Fig. 12 for both V_o and V_{gr}. The comparison is made while the central pressure values (p_c) of *both storms are within 1 kPa of each other, not necessarily when they* are the lowest value. Both V_o and V_{gr} indicate that, at this point, Super Typhoon Wynne is more "intense" than Tip at the maximum wind band (as p_c would indicate). However, Tip exhibits greater "strength" outside of 110 km. As Typhoon Wynne was downgraded from super typhoon to typhoon (with p_c = 92.5 kPa), she continued to strengthen outside of 100 km (Fig. 12). Even though the value of V_{gr} at 256 km does not seem justified, as discussed earlier, the environmental impact is evident when comparing the strength of these two storms, and central pressure seems to have little impact.

If not used quantitatively, the qualitative use of V_{gr} can approximate the characteristic strength of a tropical cyclone. Also, it may be used to determine the wind profiles of disorganized systems with

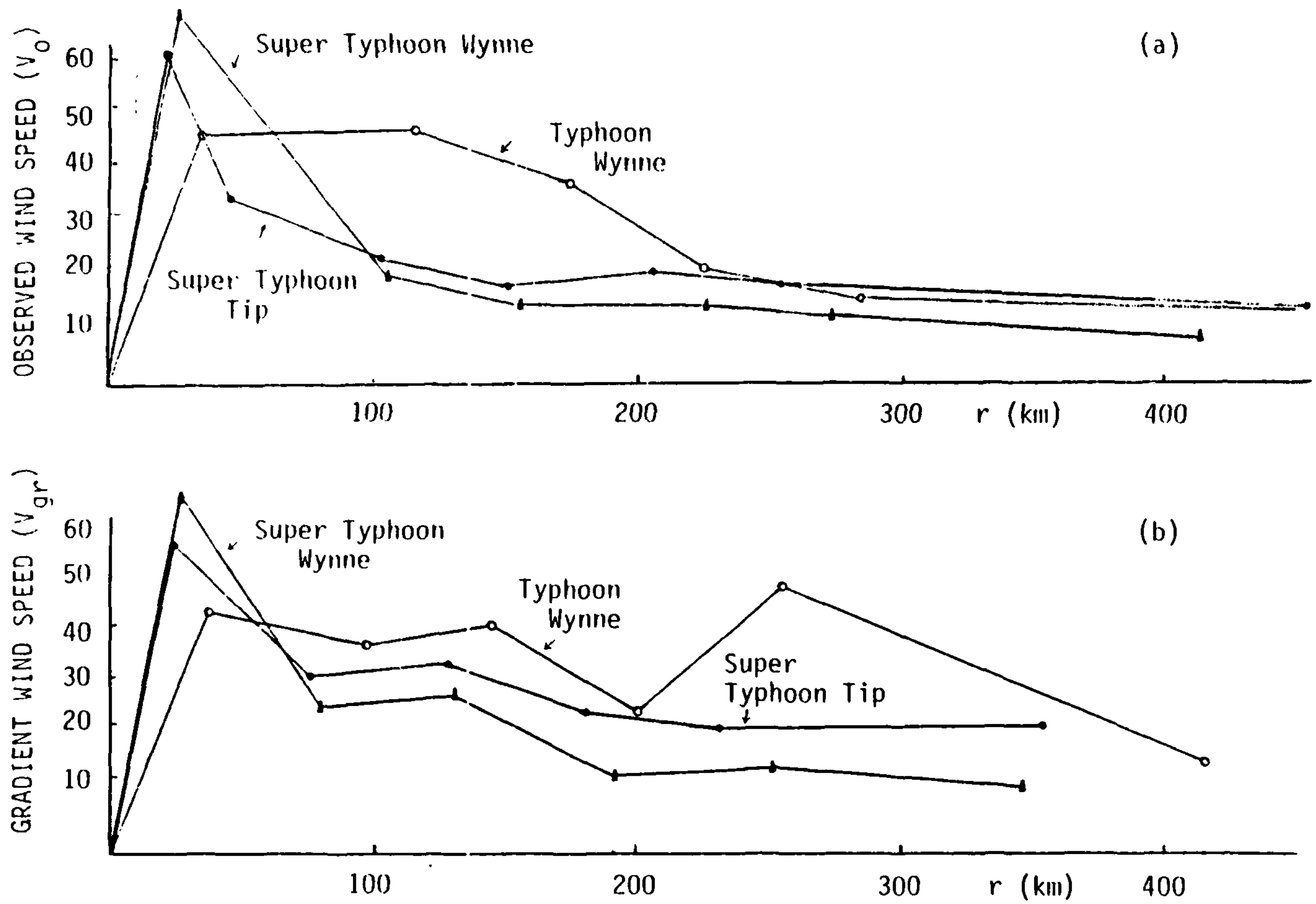


Fig. 12. Comparison of (a) V_o and (b) V_{gr} profiles for Super Typhoon Wynne (solid triangles), Super Typhoon Tip (solid circles) and Typhoon Wynne (open circles).

unusually high winds occurring well separated from the center. In order to do this accurately, a finer mesh of pressure observations will need to be constructed with accurate instrumentation and precise navigation. This is not feasible with present operational methods of typhoon reconnaissance.

C. Size

The storm size was evaluated for all tropical cyclones in the data set. Tables 6 and 7 contain a comparison of the various techniques used in estimating the size of four storms. The computer program's computation of size is compared to various manual techniques using the synoptic scale analysis that is available over the ocean. The primary synoptic means of determining size is the AROCI technique discussed in Chapter III. The Daily Weather Maps of the Japan Meteorological Agency were used for the synoptic scale surface analysis. On this scale, which is the only scale available over data sparse oceans, the outer closed isobar was nearly always analyzed as 100.8 kPa. Therefore, an accurate estimate of the actual outermost closed isobar value was not always possible. Yet, using 100.8 kPa, the AROCI values are listed in the third column of the tables.

Often, the 100.8 kPa isobar was extremely elongated. This would tend to yield unrealistically large values for the AROCI. When this was the case, the next lower symmetric isobar at pressure p was subjectively approximated by interpolation between analyzed values to compute the average radius of the outermost closed symmetrical isobar (AROCSI). These values were preferred over the AROCI and also are listed in the

Table 6. Comparison table of storm size computation methods for tropical depressions and tropical storms. The table compares the program's computed radius (r'), the AROCI using 100.8 kPa, the AROCI using a variable pressure (p'), and the average radius of the outer closed symmetrical isobar (AROCSI) at pressure p.

Row no.	r' (km)	AROCI (100.8 kPa) (km)	AROCSI/p (km/kPa)	AROCI/p' (km/kPa)	NAME
			DEPRESSION		
1.	306	363	-	165/100.5	DOM
2.	461	265	-	552/101.1	DOM
3.	326	219	-	363/100.9	FORREST
4.	189	222	-	400/101.0	FORREST
5.	265	222	-	-	FORREST
6.	294	267	-	457/101.0	FORREST
7.	889	544	-	193/100.6	TD14
			TROPICAL STORM		
1.	235	372	-	268/100.6	DOM
2.	237	417	-	354/100.7	DOM
3.	415	698	524/100.6	-	DOM
4.	345	578	-	-	DOM
5.	237	-	-	469/100.7	DOM
6.	402	-	-	485/100.7	DOM
7.	180	244	-	-	FORREST
8.	463	270	-	-	FORREST
9.	222	217	-	531/101.0	FORREST
10.	146	137	-	-	FORREST
11.	293	407	-	-	TIP
12.	443	1141	420/100.4	913/100.7	TIP
13.	396	1151	354/100.4	1151+/100.9	TIP
14.	243	930	257/100.4	330/100.5	TIP
15.	754	931	293/100.4	-	TIP

Table 7. As Table 6, except for typhoons and super typhoons.

Row no.	r' (km)	AROCI (100.8 kPa) (km)	AROCSI/p (km/kPa)	AROCI/p' (km/kPa)	NAME
			TYPHOON		
1.	204	500	212/100.5	-	DOM
2.	261	394	-	-	DOM
3.	281	444	-	-	DOM
4.	304	670	333/100.4	-	DOM
5.	293	467	-	319/100.6	DOM
6.	233	-	-	303/100.4	DOM
7.	207	1004	394/100.4	533/100.5	TIP
8.	843	861	-	-	TIP
9.	454	944	-	-	TIP
10.	1104	1044	-	-	TIP
11.	2735	1030	-	-	TIP
12.	959	1053	-	754/100.4	TIP
13.	928	1076	-	839/100.6	TIP
14.	2076	985	-	-	TIP
15.	1011	846	-	-	TIP
16.	972	937	-	-	TIP
			SUPER TYPHOON		
1.	1870	1050	-	-	TIP
2.	639	1161	-	-	TIP
3.	572	1143	-	-	TIP
4.	1470	1222	-	-	TIP
5.	725	1176	-	-	TIP

tables when extreme elongation of the 100.8 kPa isobar occurred.

As mentioned earlier, the program automatically assumes that the outer limit of the storm has been reached when flight level and surface winds drop below 13 and 11 m s^{-1} respectively. Initially, the pressure at the outer limit of the storm (p') is assumed to be 100.8 kPa; however, when the above wind limits are reached at lower pressures, the program uses this new value of p' in all computations. Conversely, when winds at higher pressure values (p > p') are above 18 and 13 m s^{-1} respectively, p' is changed upward. The synoptic analysis of the AROCI using p' is then estimated and given preference over the synoptic analysis of the AROCI using 100.8 kPa and that of the AROCSI using p as the best synoptic means of determining size.

In the tables, the preferred synoptic means of analyzing the AROCI is listed farther to the right. In the case of depressions, the differences between the computed radius (r') of p' and the analyzed AROCI values for p' suggest that the precision of the AROCI technique on the synoptic scale is questionable. It is, therefore, not advisable to regard the preferred synoptic means of computing the AROCI as absolute in defining the size of the storm.

Generally speaking, the r' values that are given in the tables compare favorably with the preferred AROCI values when p' is measured directly on one of the inbound or outbound tracks or when r' is interpolated using (A-7). However, in those cases where data were not taken at sufficient distance from the storm for interpolation, r' tends to blow up to unacceptable values. This can be seen for the last depression (row no. 7) and tropical storm (row no. 15) listed in Table 6 and for several typhoon and super typhoon cases in Table 7.

A search was made for ship reports to supplement the aircraft data. Reconnaissance data for missions flown near synoptic report times on TD 14 and Typhoon Tip were supplemented with nearby synoptic ship reports. The ship report position and pressure were added to the data so that r' could be interpolated instead of extrapolated. The corrected values of r' were computed with (A-7), using the computer's output of A and B scaling parameters, and are listed in Table 8 along with the corresponding improvement. Improvement was calculated by determining the absolute difference between r' and the preferred AROCI technique and subtracting the absolute difference between the corrected r' and the preferred AROCI technique. This is only meaningful if we assume that the preferred AROCI is the best standard for comparison. General improvement was noted for most cases, but some cases indicated degradation. However, examination of the initial reconnaissance data for the first typhoon listed in Table 8 reveals that a 100.8 kPa surface pressure was extrapolated from the 70 kPa level at 365 km from the center (versus a corrected r' value of 369 km interpolated by the program with the ship report included). This information was not used in the original computation of r' because the scaling parameters had not yet been computed. However, it does show that the AROCI technique, in itself, is subject to considerable error without the use of aircraft and ship information. Very little ship pressure information was incorporated into the Japanese analysis even though ship wind reports were used.

When the contents of Table 8 are plotted for Typhoon Tip in its typhoon and super typhoon stages (Fig. 13), the extreme variation of the

Table 8. Improvement of r' computation with the addition of synoptic ship reports.

r' (km)	Preferred AROCI/p (km/kPa)	Corrected r' (km)	Improvement (km)	Name (row no.)	
		DEPRESSION			
889	193/100.6	269	620	TD14	(7)
		TROPICAL STORM			
415	524/100.6	569	64	DOM	(3)
345	578/100.8	409	64	DOM	(4)
		TYPHOON			
843	861/100.8	369	-474	TIP	(8)
454	944/100.8	746	292	TIP	(9)
1104	1044/100.8	1135	- 31	TIP	(10)
2735	1030/100.8	748	1423	TIP	(11)
959	754/100.4	725	176	TIP	(12)
928	839/100.6	1050	-122	TIP	(13)
2076	985/100.8	815	921	TIP	(14)
1011	846/100.8	468	-213	TIP	(15)
972	937/100.8	502	-400	TIP	(16)
		SUPER TYPHOON			
1870	1050/100.8	730	500	TIP	(1)
639	1161/100.8	1226	457	TIP	(2)
572	1143/100.8	1065	493	TIP	(3)
1470	1222/100.8	928	- 46	TIP	(4)
725	1176/100.8	1113	388	TIP	(5)

Note: Numbers in parentheses in the right column refer to row numbers in Table 6 (for depressions and tropical storms) and Table 7 (for typhoons and super typhoons).

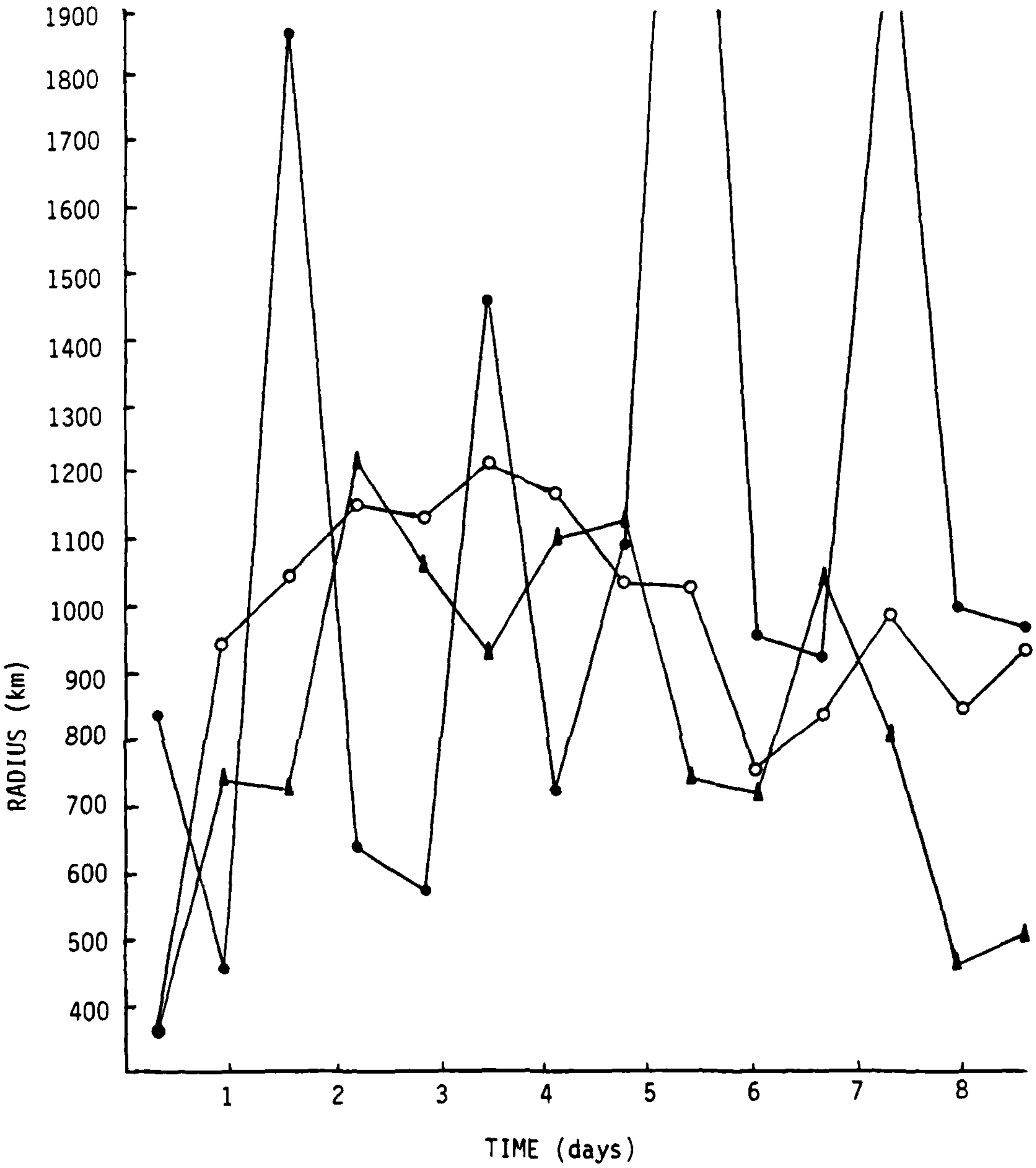


Fig. 13. Comparison of the values of r' (solid circles), corrected r' (solid triangles), and preferred AROCI technique (open circles), for those cases in Super Typhoon Tip's life cycle for which p' and r' were extrapolated.

uncorrected computer values of r' is evident. With the addition of only one ship report per mission, the size increase of the storm is very evident and a considerable smoothing is realized. With the addition of more supplemental surface reports into the model (either aircraft, ship, or surface observation) the model will be able to portray storm size in real time.

CHAPTER VI

CONCLUSIONS

The ability of routine aircraft reconnaissance data to depict accurately the intensity, strength, and size characteristics of western North Pacific tropical cyclones was studied for representative tropical cyclones of 1979-1980. Based upon a statistical analysis of the usefulness of aircraft wind observations and a comparison with computed gradient winds (using the pressure data), the following conclusions are made.

When observed winds (instrumentally measured and visually estimated) are correlated with the pressure data, the results show a high degree of variance. This is attributed to various instrumental, observational, and navigational shortcomings. These shortcomings prevent the data from being used to develop empirical relationships, since the resultant data distributions do not resemble normal distributions. Certain steps may be taken to "sanitize" the data of some of the observational shortcomings. For example, data could be sorted or classified to include those observations which are taken along tracks roughly normal to the pressure gradient, but to exclude observations along tracks approximately parallel to the pressure gradient. The exclusion of these latter data would more than likely negate some of the problems which account for the extreme outliers in the wind/pressure gradient distributions. However, this would still leave the problems of inaccurate wind measurement/estimation and navigation. With this in mind, it is assumed that the means of collecting pressure data are far more reliable than quantitatively determining wind speed; this assumption favors the computation of gradient winds as an estimate of the local wind.

The locally computed gradient wind may be used to approximate the intensity of tropical cyclones. For classically developed typhoons, which exhibit a sharp pressure drop and maximum winds within 55 km of the center, the gradient (or cyclostrophic) wind, that is computed using the pressure gradient over this distance, underestimates the theoretical maximum winds determined by (5). However, when the radius of the storm's minimum pressure center is known, the corresponding adjustments to pressure gradient and the radius of curvature terms in the gradient (and cyclostrophic) wind equation lessens the differences between methods. With improved ability to determine the radius of negligible pressure change within the eye and with shorter distances over which to measure pressure gradients, the gradient wind method may be a better method for determining intensity characteristics of different storms with approximately equal central pressures. The main shortcoming continues to be navigational error. Gradient wind errors of as much as 6 m s^{-1} are common for the typical round off of positions to the nearest tenth of a degree. This must be improved upon to be useful.

The disorganized storms which do not exhibit classical pressure and wind profiles also may be evaluated for intensity using the local gradient wind. A review of certain cases shows that some disorganized storms exhibit maximum wind bands at considerable distances from their centers. These trends are reflected weakly by the gradient wind profiles. With higher navigational precision and a denser data collection frequency, these features may be better defined.

The computation of gradient winds at approximate 55 km intervals also may be used to estimate general strength characteristics. With the current observation interval as large as 55 km and with the current positioning error as large as 9-18 km, exact profiles are not obtainable; however, general strength patterns may be subjectively made. Actual wind measurements/estimates tend to be less than the computed gradient winds; however, the actual maximum winds between observations are likely to be missed due to a low sampling rate or measurement inaccuracy.

The fitting of known pressure data to a theoretical tropical cyclone pressure profile is used to approximate storm size. The shortcomings of trying to fit data from nonclassical or disorganized storms (i.e., depressions, tropical storms, etc.) to a classical profile are at least partially offset by internal program wind thresholds, which act as a check and balance system. However, large variations in computed size values point out the need for the following:

1) Since extrapolation of radial size results in the most variation, data should be collected at the 70 kPa level at least as far out from the center as the storm's radial size (r'). This would avoid the need for extrapolation of the radial size using (A-7).

2) If extrapolation is necessary, subjective determination of p' and p_n may be necessary in order to avoid excessive error in the size computation. Small differences (on the order of 0.1 kPa) in p' or p_n may cause significant differences in computed size under these circumstances.

3) Supplementing aircraft data with as little as one ship report or surface report provides an excellent means of avoiding extrapolation.

The innermost ship or surface observation outside of r' with winds less than 13 m s^{-1} would be a good addition to the aircraft data base, provided the times of the observations are approximately the same. The ideal situation would be that the computations in all four quadrants of the storm be averaged similarly to the AROCI technique.

The operational aircraft horizontal observation system has remained essentially unchanged for over 15 years. These manual techniques of data gathering do not meet the needs of this study, much less the other prediction techniques that are currently operational. A high density horizontal weather observation system similar to the Atmospheric Distributed Data System (ADDS), being currently tested on Air Force aircraft, is necessary. With improvements in communications, navigation, data density, and data accuracy, the analysis and predictive models surely will improve.

The results of this study do not satisfy totally the original objectives as stated when the research was started (see Chapter II); however, using a more reliable data base as made available by NOAA research aircraft or the future ADDS program may show significant improvement. Of particular interest will be the improvement of V_{gr} computations with greater navigational precision and data density. Even with the likelihood of continued wind measurement errors within the tropical cyclone environment, significant gains should be possible in the near future if forward steps are taken. This program and concept of analysis is offered for future study using improved data bases soon to be available.

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APPENDIX

This Appendix discusses the data handling and processing procedures used in determining the intensity, strength, and size of the tropical storms evaluated. Information on the source of the original data is presented. The format in which the data are ordered for computation is described. The equations used in calculating are derived and explained, including descriptions of how many of the quantities are determined. Finally, the detailed computer program, including annotations, is displayed.

The data comprising the original aircraft reconnaissance observations were recorded on standard forms and archived in the National Climatic Data Center, Asheville, North Carolina. The forms for 1980-1981 were obtained from the U.S. Air Force Environmental Technical Applications Center. The data from the forms were put in a coded format which could be used in the computer process. Because of the time involved in this phase, only one year of data (1980) and the data for Super Typhoon Tip (1979) were used for this study.

The data were coded in the following format:

aa bbccc ddd eeee ffggg hhhh iijjj kkkk.

The significance of each group is:

aa - code of observation level and type
bb - consecutive day after first mission flown on storm
ccc - Greenwich Mean Time (GMT) of observation
ddd - latitude of observation in degrees and tenths
eeee - longitude of observation in degrees and tenths
ff - flight level wind direction in tens of degrees
ggg - flight level wind speed in knots
hhhh - height of standard surface in meters

ii - surface wind direction in tens of degrees
jjj - surface wind speed in knots
kkkk - sea level pressure in millibars

All data were ordered in integer format for simplicity and efficiency of computation. Further explanation of the coded data is included in the commentary portion of the Appendix.

Initially, data were taken from the input data base which was stored on disk in the format described in Chapter IV and in the Appendix. Three separate output data sets were generated and labeled according to storm name, mission number, and number of observations for the mission. Observations for an entire mission were placed into memory at one time. The times of these observations were changed from the GMT format to a continuous minute format starting at 0000 GMT of the first day that a mission was flown on a particular storm. This helped reduce the computing time required for determinations of system velocity and center position.

As the time was converted, sea level pressures were extrapolated for observations taken at the 70 kPa level. This allowed both a sea level pressure gradient and a 70 kPa height gradient to be computed. Jordan's (1958) mean summer tropical atmosphere was adjusted for temperature and relative humidity differences for the innermost 220 km of western Pacific typhoons (Table A-1) after Gray et al. (1975). This modified atmosphere (Fig. A-1) gives a standard 100-70 kPa thickness of 3063 m for the storm environment. Using this value plus the given 70 kPa height (H_{70}) for each observation outside of the center, a 100 kPa height value (H_{100}) was computed,

$$H_{100} = H_{70} - 3063 \, . \qquad \text{(A-1)}$$

Table A-1. Mean summer tropical atmosphere of Jordan (1958) adjusted for the western Pacific typhoon environment (from Gray *et al.*, 1975).

Level (kPa)	T (°C)	RH (%)	T_d (°C)	w (g/kg)	T_v (°C)
SFC	25.7	90	23.9	18.4	-
100.0	25.8	89	23.8	18.4	29.1
95.0	23.4	89	21.5	17.1	26.4
90.0	20.6	87	18.1	14.7	23.2
85.0	18.0	87	15.9	13.5	20.4
80.0	15.6	85	13.1	11.9	17.7
75.0	12.9	83	10.1	10.4	14.7
70.0	10.1	77	6.2	8.6	11.6

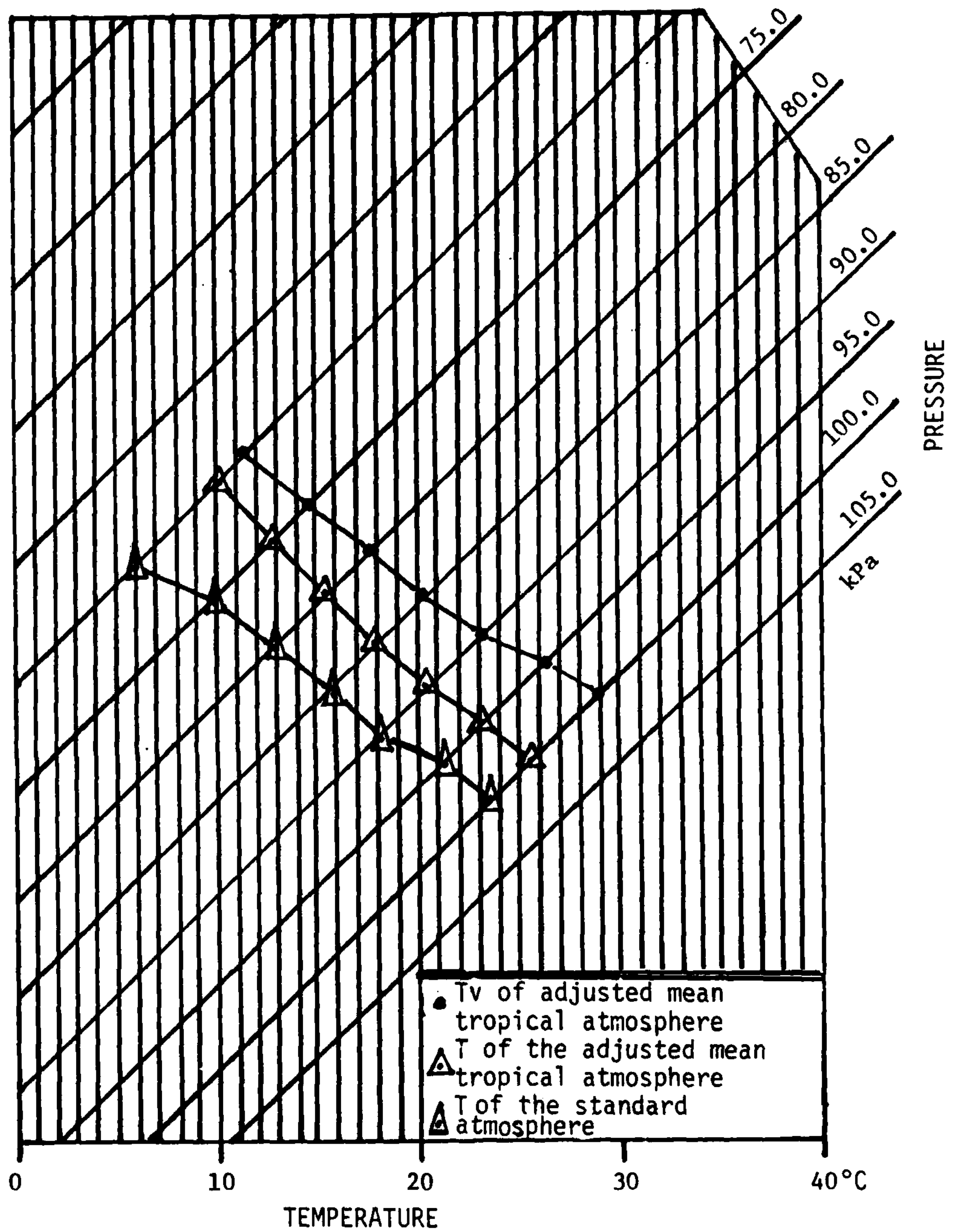


Fig. A-1. A tephigram which compares ambient and virtual temperature profiles of tropical and standard atmospheres. These profiles include the virtual temperature (•) and ambient temperature (△) profiles of the adjusted mean tropical atmosphere of the western Pacific as well as the ambient temperature profile of the standard atmosphere (▲) (after Gray et al., 1975).

The hypsometric equation was used in the form

$$H_{100}C = \ln\left(\frac{100}{p_o}\right) \quad , \tag{A-2}$$

where C is the hypsometric constant and p_o is the sea level pressure in kPa. The hypsometric constant is

$$C = g/R_d \, \overline{T}_v \quad , \tag{A-3}$$

where g is the gravitational constant, R_d is the gas constant for dry air, and $\overline{T}_v$ is the assumed mean virtual temperature between the 100 kPa level and the surface. The modified atmosphere of Table A-1 indicates that T_v is 29.1°C at 100 kPa and this is a realistic approximation of $\overline{T}_v$ for most cases. Using this to establish C and rearranging gives

$$p_o = 100 \, / \, [\exp \, (H_{100}C)] \tag{A-2a}$$

as the sea level pressure in the tropical cyclone environment outside of the center.

When a fix was made of the 70 kPa level circulation center without the benefit of a minimum sea level pressure observation at the surface center (p_c), minimum sea level pressure was extrapolated from 70 kPa using the 70 kPa center minimum height and the Jordan (1957) formula,

$$p_c = .115(H_{70}) + 645 \quad . \tag{A-4}$$

This relationship works well even when surface and 70 kPa centers are separated horizontally, even a significant distance. It is preferred to the former method of computation because of the variability of temperature and 100-70 kPa thicknesses in the center environment, whereas these elements are fairly constant outside of the center of most storms.

Since the program may be used in near real time situations, a means of determining system velocity and position needed to be developed using only reconnaissance data, without relying on the best track or forecast values. The goal was to make the program as self-sufficient as possible. In the second part of the program, the data were searched for flight level and surface center observations. The times and positions of these observations were then used to compute the movement of the system. The velocity of the system was computed by determining the changes in latitude and longitude between fixes. With the fix positions, fix times, and system velocities in computer memory, a center position could be computed for any time.

In part 3 of the program, the following computations were necessary. First, a determination was made of the difference between the current observation time and the next future fix time (or the last fix time of the storm). Once this was determined, the system fix positions and velocities that were stored in computer memory were used to compute the current center positions (both flight level and surface). Each individual observation was then plotted relative to the current center position.

In order to compute wind and pressure gradient relationships, observations must be normalized to the pressure field. If assumption is made that (for the tropical cyclone environment) the pressure field is symmetrical about the center, then the normalization can be accomplished by transposing observations to a common radial line from the center. The assumption of pressure symmetry is realistic for the tropical cyclone mission, considering the small distances between most observations.

In Fig. A-2, a situation where two consecutive observations undergo transposition is seen. Observation 1 is positioned at angle $\emptyset_1$ and radial distance r_1 at time t_1. Observation 2 is positioned at angle $\emptyset_2$ and radial distance r_2 at time t_2. It can be seen that these two observations do not initially fall on a common radial line from the center unless we transpose observation 1 to a position at distance r_1 along the radial line through observation 2 and the center of the cyclone. By rotating observation 1 through an angle, $\beta = \emptyset_2 - \emptyset_1$, it arrives along the radial line through observation 2 at radial distance r_1 and time t_2. During this process, the pressure of observation 1 (p_1) remains constant since we assumed symmetry. However, the wind direction of the transposed observation must be adjusted for the angle of transposition (β). Now a realistic pressure gradient can be attained since Δp is normal to the symmetric pressure field.

Observed winds must also be corrected for system motion before being used in the computations. The absolute velocity of the wind consists of that portion due to the pressure gradient and the component due to the system's motion. To adjust the winds to a relative velocity, a sub-program was written which split each observed wind velocity into u and v components and subtracted the u and v component of the system motion. The transposition of observation 1 was then made through angle β with a corresponding correction to the wind direction.

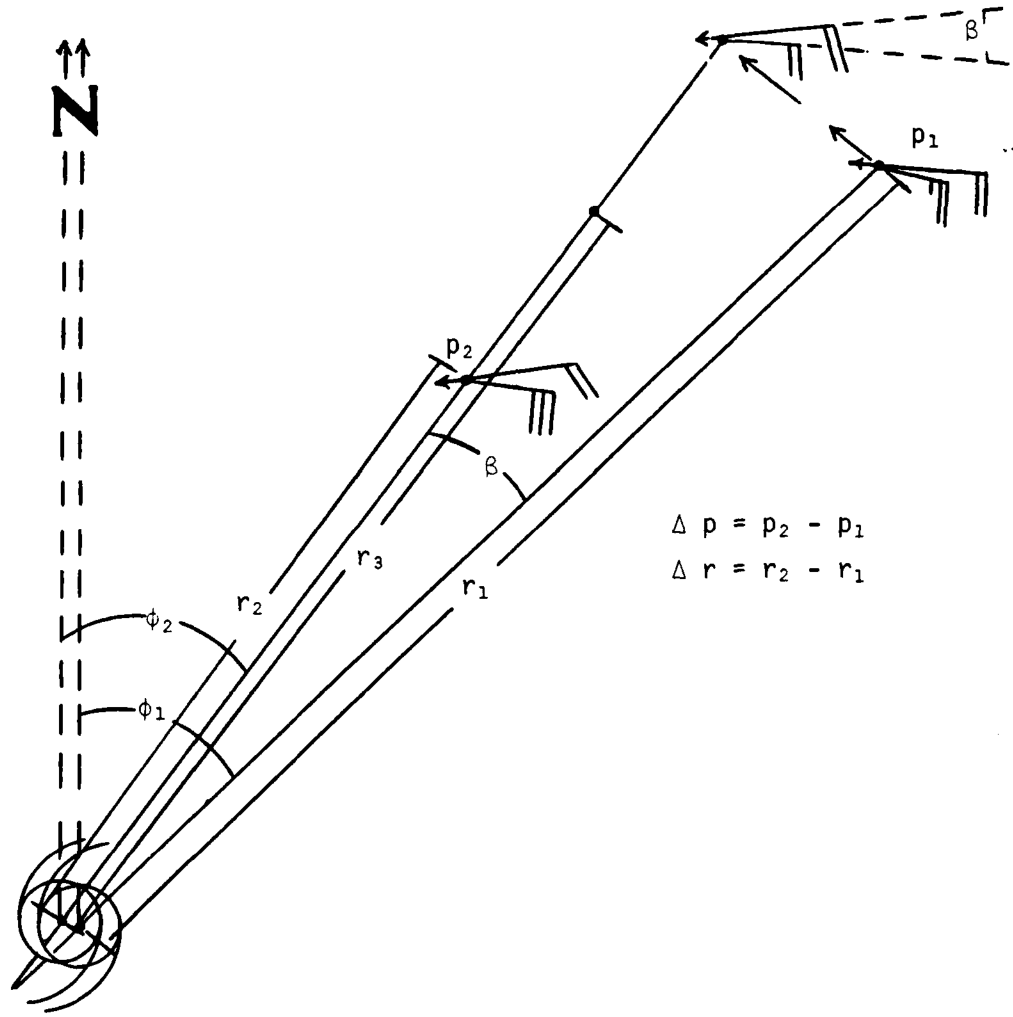


Fig. A-2. The transposition of observations to a common radial line normal to a symmetrical pressure field. Observation 1 at angle ϕ_1, radial distance r_1, and pressure p_1, is transposed to the same radial line as observation 2 at angle ϕ_2, radial distance r_2, and pressure p_2. The angle β is the angle of transposition of observation 1 to the same radial line as observation 2.

When consecutive observations contained pressure/height data, the pressure/height gradient was compared to the observed winds. Now that the observations and winds are transposed to a common radial, the gradient and winds may be correlated. To do this, the maximum wind between the two observations as well as the average wind were computed. These data were then interpolated to a midpoint position between the two observations; they represent the average and maximum winds which are associated with the pressure/height gradient at radial distance r_3 (Fig. A-2).

On occasion, consecutive observations do not contain pressure/height data. This occurs most frequently on low level missions where midpoint winds are taken between pressure observations. When this occurred, the program transposed the previous observations with pressure/height data and one intermediate wind observation (Fig. A-3). All three transposed winds were evaluated to determine average and maximum winds, which in turn were correlated to the gradient.

It must be remembered that simultaneous correlations of flight level and surface level winds and gradients were computed. This was necessary because of the frequent vertical tilt observed in tropical cyclones (Fig. A-4). Problems arise when we extrapolate sea level pressures from the 70 kPa level and try to infer gradient relationships under these circumstances. It is safe to assume that under most circumstances when vertical tilt is not extreme, the sea level pressure extrapolation is fairly accurate and the sea level pressure gradient (SLPG) can be computed with reasonable accuracy. However, for locations within a one degree of latitude radius of the vortex center, the tilt of the

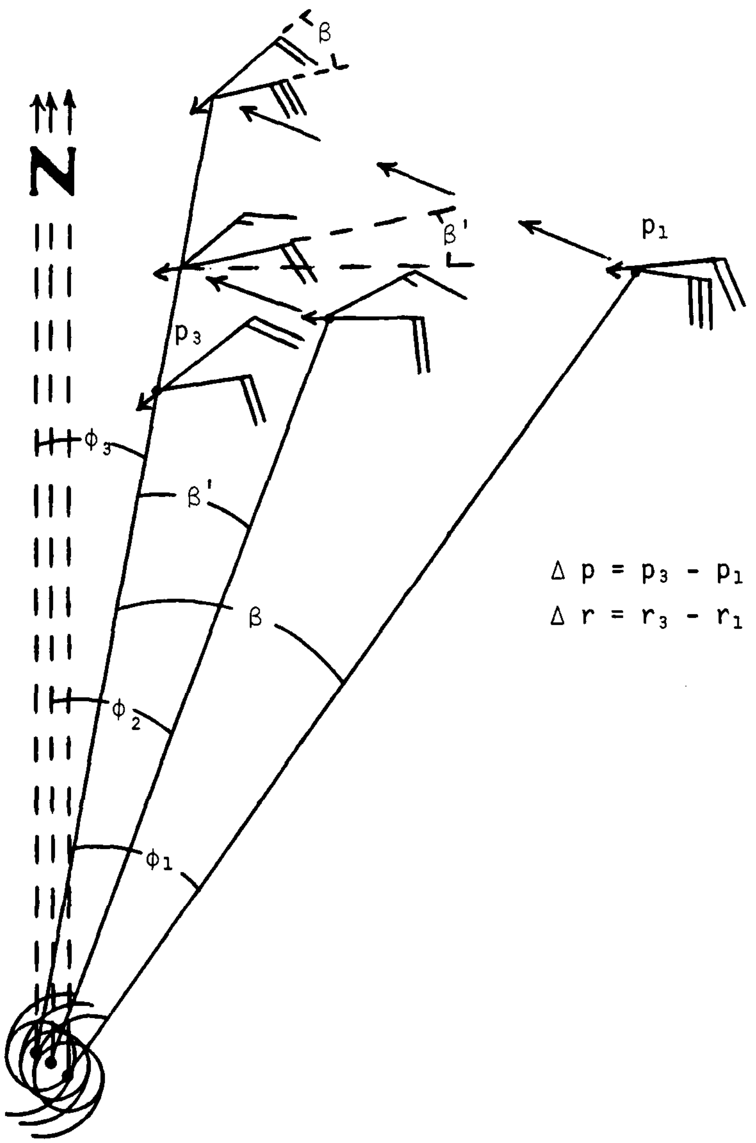


Fig. A-3. As in Fig. A-2, except with an intermediate observation (observation 2) without pressure data. The angle β' is the angle of transposition of the intermediate observation to the same radial line as observation 3.

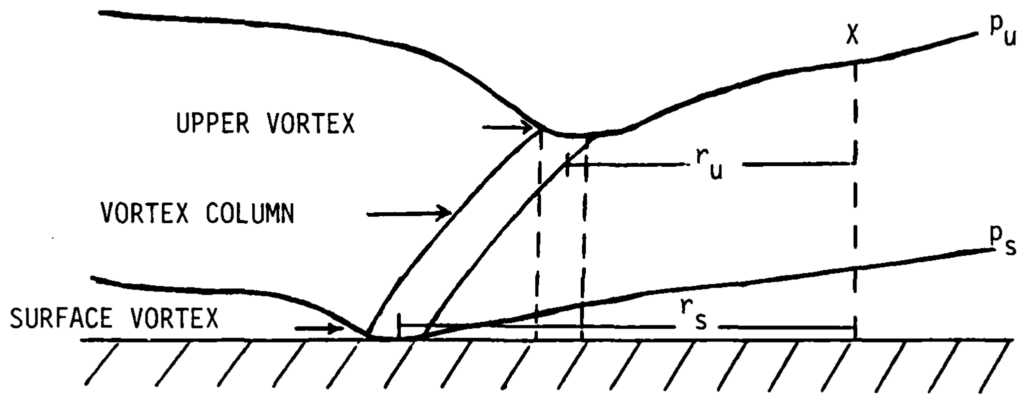


Fig. A-4. Vertical tilt of a tropical cyclone vortex between two pressure levels. The observation point (X) is a certain distance (r_u) from the vortex center at the flight pressure level (p_u) and a greater distance (r_s) from the surface vortex center. The surface center's pressure level (p_s) is shown as it slopes upward with distance from the center.

vortex may significantly influence the actual SLPG. When the tilt is extreme, the accurate determination of SLPG is further complicated, yet under these circumstances, the tropical cyclone is usually poorly organized, and the winds are generally light.

With maximum and average flight level winds available for nearly every set of observations, correlations between these winds and the flight level height gradient (FLHG) were determined. If surface winds were observable, correlations were drawn between the FLHG and the maximum and average surface wind. In addition, with sea level pressure extrapolated from 70 kPa heights, surface wind correlations with the SLPG were possible.

After these correlations were determined, data were distributed to two of the three output files. Output file number one contained the input data with: 1) the time converted to continuous minute format, 2) the latitude and longitude, 3) the flight level and surface winds corrected for system motion, and 4) the sea level pressure (extrapolated from 70 kPa heights if necessary). The second output file contained distances from the flight level and surface centers to the midpoint between observations with pressure/height data. It also listed the total correlations, which consisted of: 1) average flight level wind with the FLHG, 2) average flight level wind with the SLPG, 3) maximum observed flight level wind with the FLHG, 4) maximum observed flight level wind with the SLPG, 5) average surface wind with the FLHG, 6) maximum observed surface wind with the FLHG, 7) average surface wind with the SLPG, and/or 8) maximum observed surface wind with the SLPG.

If the results prove meaningful, the analysis of tropical cyclone intensity and strength characteristics may be done using the wind and gradient correlations described above. Intensity may be approximated by determining the maximum gradient and relating it to a maximum wind value. Strength may be determined by averaging the gradient at specified radial distances from the cyclone's center. The averaging would go out to the limit of the cyclonic circulation, and an average strength could be computed. However, in order to analyze tropical cyclone size, the program must go further.

First, a definition of size must be determined. Ideally, the size is determined by the average radius outside which any tropical cyclone effect is negligible. Practically, this has been done in the past by evaluating the average radius of the outermost closed isobar (Merrill, 1982). An analysis of this type may be done provided that the synoptic and ship reports will allow an accurate pressure analysis. However, in some parts of the ocean, this is hard to accomplish.

One of the objectives is to determine tropical cyclone size in near real time. The best approach incorporates the Holland (1980) hurricane/typhoon wind and pressure profile equation,

$$r^B \ln[(p_n - p_c) / (p - p_c)] = A \quad , \qquad \text{(A-5)}$$

where r is the radial distance from the center, p_n is the environmental pressure (theoretically at infinite radius), p_c is the central pressure, p is the pressure at radius r, and A and B are scaling parameters. Rearranging this equation yields

$$r = \{A / \ln [(p_n - p_c) / (p - p_c)]\}^{1/B} \quad . \qquad \text{(A-6)}$$

Fig. A-5 approximates the family of rectangular hyperbolas which represent the pressure profiles of various typhoons. If p' is substituted for p in (A-6) and set at the tropical cyclone's assumed outermost closed isobar value, then we can substitute r' for r as the storm's radius and solve for r' once A and B are established. The equation then becomes

$$r' = \{A / \ln [(p_n - p_c) / (p' - p_c)]\}^{1/B} \quad . \qquad \text{(A-7)}$$

The scaling parameter B determines the shape of the profile and varies between about 1.0 and 2.5 for most typhoons. The stronger the pressure gradient at the radius of maximum wind, the higher the value of B. For this study, Holland's minimum limit of B has been lowered from 1.0 to 0.5 in order to consider the weaker pressure gradients of subtyphoon systems. In the program, B can best be approximated by measuring the innermost (0-55 km) pressure gradient (IPG) and translating it into a corresponding value of B. Using the observed extremes (weak and strong) of IPG for the 1980 data, a sub-program was developed which could interpolate a value of B from between 0.5 and 2.5 for every fix (measured IPG).

Once B is determined, a value of A may be determined by solution of (A-5) with values of r and p known. Solving for r' in (A-7) then gives the storm's radial size.

Representative values of p_n and p' are critical to the accurate computation of size (r'). A method to determine objectively p_n and p' was included in the program. However, as discussed later, this may be done best, subjectively. The objective method makes use of the Atlas of

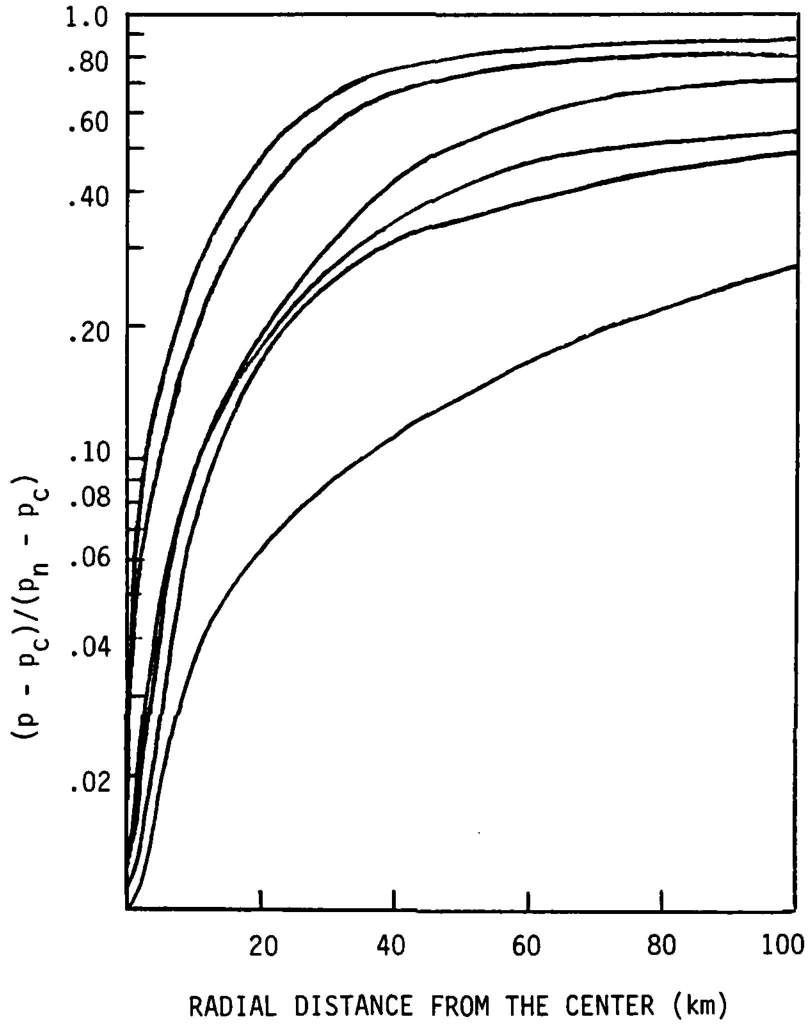


Fig. A-5. Pressure profiles of randomly selected typhoons used in this study. The parameter $(p - p_c)/(p_n - p_c)$ is used to normalize the profiles for variations due to different central and environmental pressures.

Mean _Sea-Level_ _Pressure_ (Chary, 1982) for the determination of mean environmental pressures at latitudes equatorward of 30°. Environmental pressure, as used here, is defined as the pressure at infinite radius from the storm. Fig. A-6 shows a typical SLP pattern for the western North Pacific in October (peak of the tropical cyclone season). As would be expected from the theory of the general circulation of the atmosphere, low pressure near the equator increases to high pressure near 30 degrees latitude (subtropical ridge) and then decreases toward 60 degrees latitude. A value of 101 kPa is a reasonable year round estimate of environmental pressure in the equatorial region. However, at 30°N the pressure varies seasonally as well as longitudinally. We can suppose that the environmental pressure at 30°N is at least as high as the central pressure of the subtropical ridge. With a tropical cyclone breaking through the ridge axis, the east-west pressure profile will be largely determined by the central strength of the subtropical ridge. Additionally, in the mid-winter months, the strenghtening of the continental high pressure of Asia may increase environmental pressures at 30°N to over 102.7 kPa. Because of this and other factors (to be described later), a value of 102.7 kPa was chosen as the environmental pressure at 30°N. The value of p_n can then be expressed as a sinusoidal function of latitude with an amplitude of 1.7 kPa between the equator and 30°N.

To demonstrate a point, two hypothetical cyclones are positioned as shown in Fig. A-6. One cyclone (A) is breaking through the subtropical ridge on a northerly track, and the other cyclone (B) remains embedded in the easterlies south of the subtropical ridge. Evaluating an east-

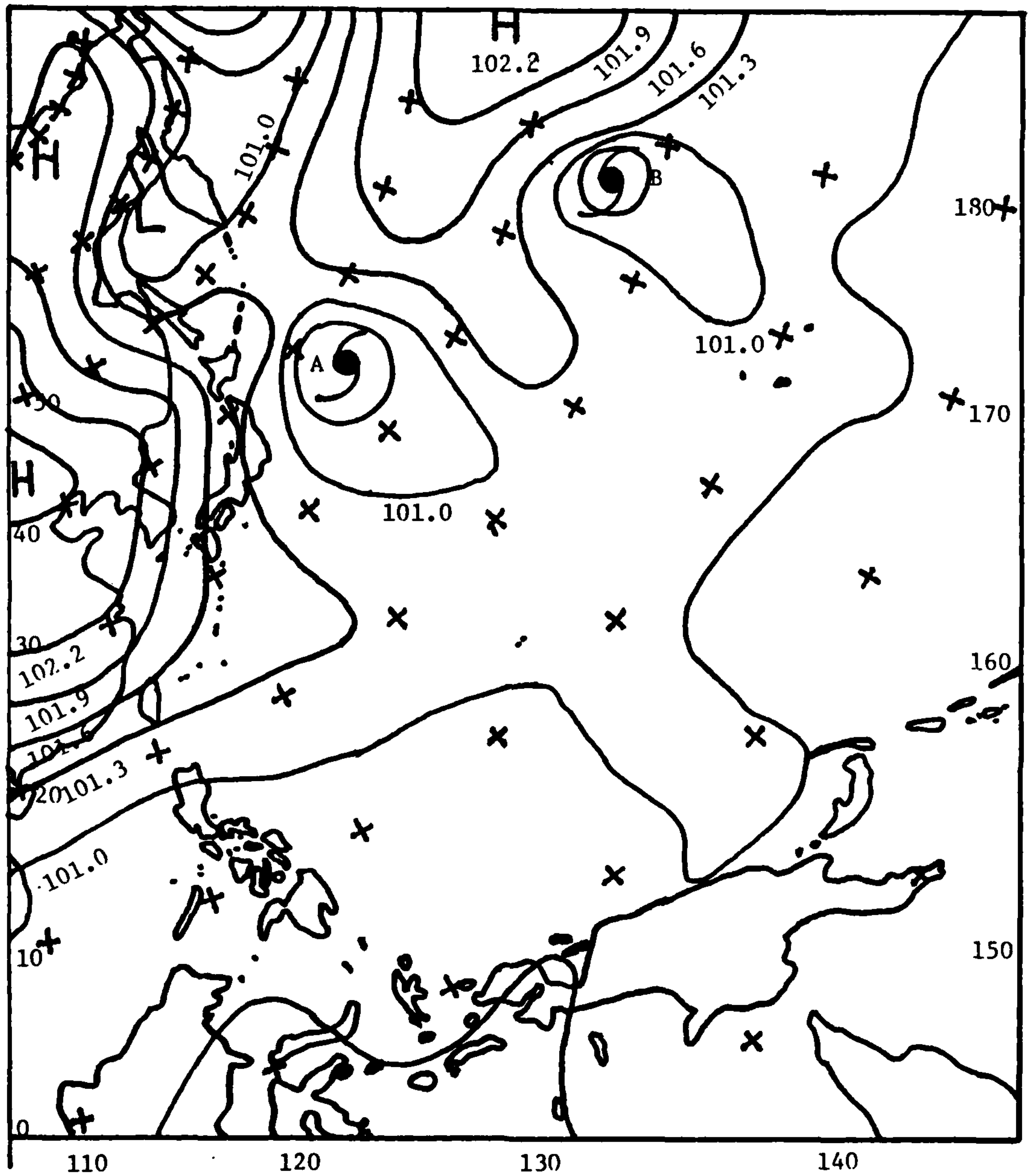


Fig. A-6. Two tropical cyclones positioned in a typical western North Pacific sea level pressure field for October (after Chary, 1982). Isobars are labeled in kPa.

west cross section of pressure for cyclone A shows that p_n increases to over 102.4 kPa in China and to over 102.2 kPa in the central Pacific. A north-south cross section of the same cyclone, on the other hand, shows a significantly smaller increase (to about 101.2 kPa in the north and to 101.1 kPa in the south). Using the sinusoidal relationship discussed previously, the computer program determines p_n to be 102.2 kPa (based on the latitude of the cyclone), which would compare well with the east-west cross section. Evaluating cyclone B in the east-west cross section indicates that p_n increases to over 101.9 kPa in the central Pacific and to over 101.6 kPa to the west. Evaluating the north-south cross section shows a p_n of nearly 102.1 kPa to the north and only 101.0 kPa to the south. The computer program determines that, for the latitude of cyclone B, p_n is 102.1 kPa, which may be too high for all but the northern quadrant in this case, but it is *climatologically* reasonable.

Although subjective determination of p_n may be the best procedure in some cases, an adequate subjective analysis of the environmental pressure is not always available in real time. Added to this, as will be discussed later, is the fact that maintaining a steep rate of increase between p_c and p_n is advantageous in size computations, and the program determinations of p_n tend to favor these steep increases.

As program execution was running, no size computations were performed until the initial center fix for any particular mission was made. At that time, a measurement of the IPG was available for the approximation of B. During every fix thereafter, a new measurement of IPG and approximation of B was made until the end of the mission. Once the initial approximation of B was available, computations of r' were made after every observation where pressure gradient was obtained as long as the radial distance from the storm's center to the observation was greater than that of a previous computation. To do this, the scaling parameter A was solved in (A-5) using the observation's radial distance as r, the observation's sea level pressure as p, and a time interpolated or extrapolated value of central sea level pressure based on the known fix values for p_c. Equation (A-7) was then solved for r' with p' set at an assumed value.

The ideal method of determining tropical cyclone size is to measure it directly. As this cannot be done in real time for most storms, the use of (A-7) was the best method of approximation. Fig. A-7 shows that if the observation point is outside the radial limit (or outermost closed isobar) of the storm (i.e., $r > r'$) and if all data indicate that p' is set accurately, then interpolation can be used to determine accurately where p' is (in terms of r') along a radial from the center. However, if p' is not accurate, r' will be inaccurate as well due to the shallow slope of the curve. If $r < r'$, then extrapolation must be used to estimate the size. This can be very difficult, because very small errors in p_n and/or p' can cause very large errors when r' is extrapolated, unless r is close enough to r' so that the extrapolation is over only a very short distance. For these reasons, only the computation made at the greatest distance from the storm's center was used in size computations.

As can be seen in Fig. A-7, if p' was incorrectly computed too large and the outermost observed pressure (p) was within p' ($r < r'$), then r' may be grossly inflated. Effort has been made to avoid this

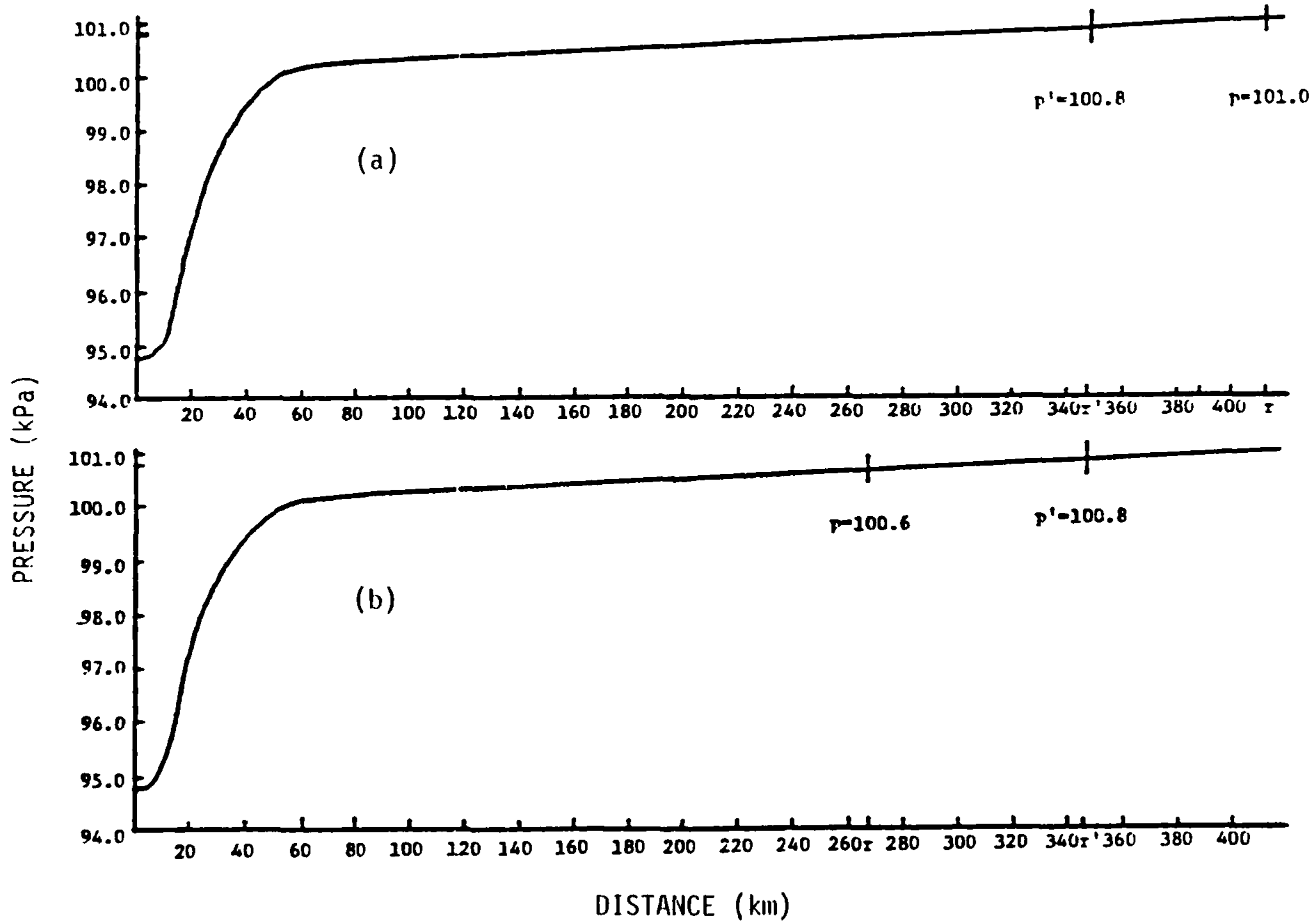


Fig. A-7. Comparison of the relative pressures (p) and radial distances (r) of observations used to define the outer limit pressure (p') and size (r') of a tropical cyclone. In (a), the radial distance (r') of the assumed outermost closed isobar value (p') is interpolated along the curve, and in (b) it is extrapolated.

circumstance by carefully adjusting p' in the program. The program started by assuming p' was 100.8 kPa. This is a reasonable value to expect for the outermost closed isobar on synoptic analyses of western North Pacific tropical cyclones. Using the combined 1980-1981 data from non-storm related observations of flight level and surface wind, mean characteristic values for the western North Pacific are 13 and 11 m s^{-1} respectively. If both flight level and surface winds dropped below these threshold values at r (with pressure p) when $p < 100.8$ kPa, it was assumed that $p' = p$. Conversely, if $p > 100.8$ kPa and if either flight level or surface winds were above 18 or 13 m s^{-1} respectively, then the winds were considered to be influenced by the cyclone, $p' = p$, and the process continued for larger values of p and r until flight level and surface winds dropped below the 18 and 13 m s^{-1} thresholds. Since the computed wind velocities in the program had system velocity subtracted, velocities above or below the thresholds were used to indicate the presence or absence of tropical cyclone effect and to adjust p'.

In addition to the above procedure, p_n was never allowed to be closer than 0.3 kPa from p'. This helped avoid extremely shallow slopes between p' and p_n at low latitudes and helped prevent inflation problems when extrapolating r'.

Even when precautions were taken to avoid inflation of r' when extrapolating, the majority of all tropical cyclone missions were flown totally within r', and therefore, extrapolation, and consequently inflation, does occur. The effects of this inflation are most noticeable when successive size computations are observed to exhibit a large variance. In order to avoid this variation, the reconnaissance data may be supplemented by a ship report (if available) at some distance (r_g) greater than the outermost reconnaissance observation and preferably greater than r'. Provided that the observation time is reasonably coincident with the reconnaissance observations in the same quadrant of the storm, the observation may be added in with the data and will allow r' to be interpolated instead of extrapolated.

Subjective substitution of p' and p_n will help smooth the irregularities of this rather mechanical program size computation. The program has a tendency to exaggerate the impact of the wind thresholds described earlier in determining p'. For example, considering tropical cyclone B in Fig. A-6, the resulting pressure field is highly asymmetric with stronger gradients and winds in the northern quadrant. If the only track into and out of the storm is from the south, even a storm with 20 m s^{-1} winds to the north may possess less than 10 m s^{-1} winds well in toward the center on the south side, even though the actual, average storm radius extends outward a considerable distance. Under these circumstances the program tended to decrease p' toward p_c until 11 m s^{-1} surface winds or 13 m s^{-1} flight level winds were encountered. Without the counter effect of a track to the north of the storm, the computed radius of the storm would be an underestimate.

The calculations and procedures described in the preceding pages were combined into a computer program developed and used to determine tropical cyclone vortex motion and vertical tilt as well as cyclone strength, intensity and size. The program also allowed computation of desired pressure/wind relationships. The program was written in basic Fortran for the Harris 100 computer at the Department of Meteorology, Texas A&M University. The data, program, and output are recorded on magnetic tape.

A commented copy of the program follows.

AUTHOR: CHARLES B. STANFIELD
PROGRAM: TROPICAL CYCLONE WIND/PRESSURE STUDY
PURPOSE: THIS PROGRAM PLOTS WINDS AND PRESSURES VERSUS RADIAL DISTANCE FROM THE CENTER OF A TROPICAL CYCLONE VORTEX. IT WILL DETERMINE CHARACTERISTIC PRESSURE/HEIGHT GRADIENTS AND RELATE THEM TO THE OBSERVED WIND FIELD. THESE RELATIONSHIPS CAN THEN BE USED TO QUANTIFY TROPICAL CYCLONE INTENSITY, STRENGTH, AND SIZE. A BRIEF DESCRIPTION WILL PRECEDE EACH PART OF THIS PROGRAM, AND A VARIABLE LIST WILL ALSO BE GIVEN.

INTEGER/REAL/CHARACTER/DATA STATEMENTS************************

```
INTEGER CODE(30,50),TIME(30,50),FLW(30,50),HSS(30,50),SFW(30,50),
.SLP(30,50),SFLG,SMIN1,LCMIN(60),SCMIN(60),DIFTIM,N(30),NUM(30),
.FLANG1,FLANG2,FLANG3,SLANG1,SLANG2,SLANG3,SCSLP(60)
REAL LAT(30,50),LON(30,50),LLAT1,LLON1,LVELAT,LVELON,LCLAT(60),
.LCLON(60),LCVLAT(60),LCVLON(60),SCLAT(60),SCLON(60),SCVLAT(60),
.SCVLON(60),DISLLA(50),DISLLO(50),DISSLA(50),DISSLO(50),LCKLAT,
.LCKLON
CHARACTER*7 NAME
DATA K1,K2,K3,C1,C2,C3,C4,C5/1000,10,90000,57.296,3598.14,
.59.969,3063.,.000113/
```

PART 1***

THE DATA ARE FILED UNDER INPUT. THE DATA BEGINS WITH A CODE TO DESIGNATE THE STORM (I.E. 80000010NE 6). THIS EXAMPLE DESIGNATES THE STORM TO BE FROM 1980 (80), WITH NUMERICAL DESIGNATION ONE (00001) AND NAME "ONE". SIX SEPARATE RECONNAISSANCE DATA SETS FOLLOW (6). EACH SEPARATE DATA SET BEGINS WITH A CODE (I.E. 8002001 20), WHERE THE "02" REPRESENTS THE MISSION NUMBER. THE "20" REPRESENTS THE NUMBER OF OBSERVATIONS ON THAT MISSION. THE FIRST GROUP OF NUMBERS ON THE DATA LINE FOR THE INDIVIDUAL OBSERVATION IS A CODE FOR THE TYPE OF OBSERVATION (I.E. 10=700MB OBSERVATION TAKEN OUTSIDE THE CENTER, 11=LOW LEVEL (1500FT) OBSERVATION TAKEN OUTSIDE THE CENTER, 20=SURFACE CENTER OBSERVATION TAKEN FROM 700MB, 21=SURFACE CENTER OBSERVATION TAKEN FROM 1500FT, 30=700MB CENTER OBSERVATION TAKEN AT 700MB, AND 41=LOW LEVEL (1500FT) CENTER POSITION TAKEN AT 1500FT). THE SECOND GROUP OF NUMBERS INDICATES THE TIME (I.E. 010035: DAY ONE (01) OF DATA GATHERED ON THE STORM AT TIME 0035 GMT). THE THIRD AND FOURTH GROUPS REPRESENT THE LATITUDE AND LONGITUDE IN TENTHS OF DEGREES RESPECTIVELY. THE FIFTH GROUP IS WIND DIRECTION AND SPEED OF THE FLIGHT LEVEL WIND (I.E. 17017: 170 DEGREES AT 17 KNOTS). THE SIXTH GROUP IS THE HEIGHT OF THE 700MB SURFACE (WHEN GIVEN). THE SEVENTH GROUP IS THE ESTIMATED SURFACE WIND AND THE FINAL GROUP IS SEA LEVEL PRESSURE (SLP) IN MILLIBARS.

THE FIRST PART OF THE PROGRAM WILL READ THE INDIVIDUAL STORM NUMBER, NAME, AND THE NUMBER OF RECONNAISSANCE MISSIONS FLOWN. IT WILL READ AND PLACE INTO MEMORY THE INDIVIDUAL MISSION NUMBER, THE NUMBER OF OBSERVATIONS FOR EACH MISSION, AND THE INDIVIDUAL OBSERVATIONS FOR THE ENTIRE STORM. THE CODED TIME WILL BE CONVERTED INTO A CONSECUTIVE MINUTE STARTING AT 0000Z ON THE FIRST DAY THAT DATA WAS GATHERED ON THE STORM. THIS TIME CAN THEN BE USED IN SYSTEM VELOCITY COMPUTATIONS. THE DATA IS ALSO MANIPULATED TO EXTRAPOLATE SLP FROM 700MB DATA, IF NECESSARY.

VARIABLE LIST********

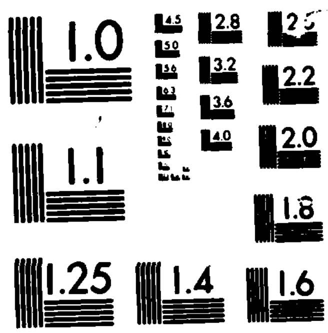
KLL - FLAG FOR 1500FT FLIGHT LEVEL
KHH - FLAG FOR 700MB FLIGHT LEVEL
NU - STORM NUMBER ID

```
NUM(K) - MISSION NUMBER ID
NAME - STORM NAME
NN - NUMBER OF MISSIONS ON STORM
N(K) - NUMBER OF OBS IN MISSION
K - DO LOOP COUNTER FOR MISSION NUMBER
I - DO LOOP COUNTER FOR OBS NUMBER
CODE(K,I) - OBS LEVEL CODE FOR OBS I OF MISSION K
TIME(K,I) - TIME OF OBS I
LAT(K,I) - LATITUDE OF OBS I
LON(K,I) - LONGITUDE OF OBS I
FLW(K,I) - FLIGHT LEVEL WIND OF OBS I
HSS(K,I) - HEIGHT OF STANDARD SURFACE FOR OBS I
SFW(K,I) - SURFACE WIND FOR OBS I
SLP(K,I) - SEA LEVEL PRESSURE FOR OBS I
ITIM - TEMPORARY TIME
MIN - TEMPORARY MINUTE OF OBS FROM DAY ONE OF THE STORM
J - COUNTER OF THE FIXES
DZ - HEIGHT OF 1000MB SURFACE
C4 - STANDARD 1000/700MB THICKNESS FOR STORM ENVIRONMENT
C5 - HYPSOMETRIC CONSTANT USING VIRTUAL TEMPERATURE CONSTANT 29.1C


98 READ(16,1,END=99)NU,NAME,NN
 1 FORMAT(I7,A7,I2)
   WRITE(17,2)NU,NAME,NN
   WRITE(18,2)NU,NAME,NN
   WRITE(19,2)NU,NAME,NN
 2 FORMAT(1X,I7,A7,I2)
   KLL=0
   KHH=0
   J=0
   DO7 K=1,NN
     READ(16,9)NUM(K),N(K)
 9   FORMAT(I7,7X,I2)
     DO8 I=1,N(K)
       READ(16,4)CODE(K,I),TIME(K,I),LAT(K,I),LON(K,I),FLW(K,I),
       HSS(K,I),SFW(K,I),SLP(K,I)
 4     FORMAT(I2,1X,I6,1X,F3.1,1X,F4.1,1X,I5,1X,I4,1X,I5,1X,I4)
 8   CONTINUE
 7 CONTINUE
   DO77 K=1,NN
     DO88 I=1,N(K)
       ITIM=TIME(K,I)
       CALL MINUTE(ITIM,MIN)
       TIME(K,I)=MIN
       IF(CODE(K,I).EQ.10)
       DZ=C4-HSS(K,I)
       SLP(K,I)=INT((1000./(EXP(DZ*C5)))+.5)
       ELSE
       IF(CODE(K,I).EQ.20)
       HSS(K,I)=HSS(K,I+1)
       IF(SLP(K,I).EQ.0)
       SLP(K,I)=INT((.115*HSS(K,I))+645.)
       ELSE
       IF(HSS(K,I).EQ.0)HSS(K,I)=INT((SLP(K,I)-645)/.115)
       END IF
       ELSE
       IF(CODE(K,I).EQ.30)
       IF(SLP(K,I).EQ.0)
       IF(CODE(K,I-1).NE.20)
       SLP(K,I)=INT((.115*HSS(K,I))+645.)
       ELSE
       IF(SLP(K,I-1).GT.800)SLP(K,I)=SLP(K,I-1)
       END IF
       END IF
       IF(HSS(K,I).EQ.0)HSS(K,I)=INT((SLP(K,I)-645)/.115)
       ELSE
       IF(CODE(K,I).EQ.21.AND.SLP(K,I).EQ.0)
```

AD-A166 417 OBJECTIVE ANALYSIS OF TROPICAL CYCLONE INTENSITY STRENGTH AND SIZE USING..(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH C B STANFIELD MAY 86 2/2

UNCLASSIFIED AFIT/CI/NR-86-28T F/G 4/2 NL



MICROCOP' CHART

```
        SLP(K,I)=SLP(K,I+1)
        ELSE
        IF(CODE(K,I).EQ.41.AND.CODE(K,I-1).EQ.21.AND.SLP(K,I).EQ.0)
        SLP(K,I)=SLP(K,I-1)
        END IF
        END IF
        END IF
        END IF
        END IF
88    CONTINUE
77  CONTINUE

    PART 2*******************************************************
    THIS PART SEARCHES THE DATA FOR FIX POSITIONS AND TIMES. IT TRACKS
    BOTH SURFACE AND FLIGHT LEVEL CENTERS WITH TIME. FOR THOSE FIXES
    WHEN ONLY A FLIGHT LEVEL CENTER IS FIXED, THE SURFACE CENTER IS
    ASSUMED TO BE DIRECTLY BELOW. THE SYSTEM VELOCITY IS COMPUTED FOR
    USE IN THE NEXT PART. CENTRAL SLP IS TRACKED SO THAT A CONTINUOUS
    ESTIMATE OF CURRENT CENTRAL SLP CAN BE INTERPOLATED.

    VARIABLE LIST**********


    TLAT - TEMPORARY LATITUDE
    TLON - TEMPORARY LONGITUDE
    SLAT1 - PREVIOUS SURFACE FIX LATITUDE
    SLON1 - PREVIOUS SURFACE FIX LONGITUDE
    SMIN1 - PREVIOUS SURFACE FIX MINUTE
    SCLAT(J) - LATITUDE OF JTH SURFACE FIX
    SCLON(J) - LONGITUDE OF JTH SURFACE FIX
    SCMIN(J) - MINUTE OF JTH SURFACE FIX
    SCVLAT(J) - SURFACE CENTER VELOCITY BASED UPON JTH FIX(LATITUDE
    COMPONENT)
    SCVLON(J) - SURFACE CENTER VELOCITY BASED ON JTH FIX (LONGITUDE
    COMPONENT)
    SCSLP(J) - CENTRAL SEA LEVEL PRESSURE FOR JTH FIX
    SFLG - SURFACE FIX FLAG
    SVELAT - COMPUTED SURFACE CENTER LATITUDE VELOCITY
    SVELON - COMPUTED SURFACE CENTER LONGITUDE VELOCITY
    JFLG - FLAG FOR FLIGHT LEVEL CENTER FIX ONLY
    LLAT1 - PREVIOUS LOW  LEVEL FIX LATITUDE
    LLON1 - PREVIOUS LOW LEVEL FIX LONGITUDE
    LMIN1 - PREVIOUS LOW LEVEL FIX MINUTE
    LCLAT(J) - LATITUDE OF JTH LOW LEVEL FIX
    LCLON(J) - LONGITUDE OF JTH LOW LEVEL FIX
    LCMIN(J) - MINUTE OF JTH LOW LEVEL FIX
    LCVLAT(J) - LOW LEVEL CENTER LATITUDE VELOCITY BASED ON JTH FIX
    LCVLON(J) - LOW LEVEL CENTER LONGITUDE VELOCITY BASED ON JTH FIX
    LVELAT - COMPUTED LOW LEVEL CENTER LATITUDE VELOCITY
    LVELON - COMPUTED LOW LEVEL CENTER LONGITUDE VELOCITY
    JJ - TOTAL FIXES FOR A STORM

    SFLG=0
    DO6 K=1,NN
      DO3 I=1,N(K)
      TLAT=LAT(K,I)
      TLON=LON(K,I)
      MIN=TIME(K,I)
      IF(CODE(K,I).EQ.20.OR.CODE(K,I).EQ.21)
      J=J+1
      IF(J.EQ.1)
      CALL EXCHG(TLAT,SLAT1,TLON,SLON1,MIN,SMIN1)
      SCLAT(J)=SLAT1
      SCLON(J)=SLON1
      SCMIN(J)=SMIN1
      SCSLP(J)=SLP(K,I)
      SCVLAT(J)=0.
      SCVLON(J)=0.
```

```
      SFLG=1
      ELSE
      CALL VEL(TLAT,TLON,MIN,SLAT1,SLON1,SMIN1,SVELAT,SVELON)
      SCLAT(J)=SLAT1
      SCLON(J)=SLON1
      SCMIN(J)=SMIN1
      SCSLP(J)=SLP(K,I)
      SCVLAT(J)=SVELAT
      SCVLON(J)=SVELON
      SFLG=1
      END IF
      ELSE
      IF(CODE(K,I).EQ.41.OR.CODE(K,I).EQ.30)
      IF(CODE(K,I-1).GT.21.OR.CODE(K,I-1).LT.20)
      J=J+1
      JFLG=1
      ELSE
      JFLG=0
      END IF
      IF(J.EQ.1)
      CALL EXCHG(TLAT,LLAT1,TLON,LLON1,MIN,LMIN1)
      LCLAT(J)=LLAT1
      LCLON(J)=LLON1
      LCMIN(J)=LMIN1
      LCVLAT(J)=0.
      LCVLON(J)=0.
      IF(SFLG.NE.0)GO TO 3
      CALL EXCHG(LLAT1,SLAT1,LLON1,SLON1,LMIN1,SMIN1)
      SCLAT(J)=SLAT1
      SCLON(J)=SLON1
      SCMIN(J)=SMIN1
      SCSLP(J)=SLP(K,I)
      SCVLAT(J)=0.
      SCVLON(J)=0.
      SFLG=1
      ELSE
      CALL VEL(TLAT,TLON,MIN,LLAT1,LLON1,LMIN1,LVELAT,LVELON)
      LCLAT(J)=LLAT1
      LCLON(J)=LLON1
      LCMIN(J)=LMIN1
      LCVLAT(J)=LVELAT
      LCVLON(J)=LVELON
      IF(JFLG.NE.1)GO TO 3
      CALL VEL(TLAT,TLON,MIN,SLAT1,SLON1,SMIN1,SVELAT,SVELON)
      SCLAT(J)=SLAT1
      SCLON(J)=SLON1
      SCMIN(J)=SMIN1
      SCSLP(J)=SLP(K,I)
      SCVLAT(J)=SVELAT
      SCVLON(J)=SVELON
      SFLG=1
      END IF
      END IF
      END IF
3     CONTINUE
6   CONTINUE
    JJ=J
    IF(JJ.GT.1)
    SCVLAT(1)=SCVLAT(2)
    SCVLON(1)=SCVLON(2)
    LCVLAT(1)=LCVLAT(2)
    LCVLON(1)=LCVLON(2)
    END IF
    J=1

    PART3*****************************************************
    THIS PART SEARCHES THE DATA FOR OBSERVATIONS AT A COMMON LEVEL
    (EITHER 700MB OR 1500FT). IT WORKS TO DERIVE PRESSURE/WIND RELA-
```

TIONSHIPS FOR BOTH THE FLIGHT LEVEL AND SURFACE. DATA FROM PART 2 IS USED TO DETERMINE THE SURFACE AND FLIGHT LEVEL CENTER POSITIONS AT EACH OBSERVATION TIME. DISTANCE OF THE INDIVIDUAL OBSERVATION FROM THE PROJECTED CENTER IS USED ALONG WITH THE ANGULAR RADIAL FROM THE CENTER TO THE OBSERVATION POSITION TO PLACE THE OBSERVATION RELATIVE TO THE SURFACE AND FLIGHT LEVEL CENTERS. LOW LEVEL (1500FT) AND 700MB OBSERVATIONS ARE HANDLED SEPARATELY. OBSERVED WINDS ARE ADJUSTED TO TAKE OUT COMPONENTS DUE TO SYSTEM MOTION. THESE WINDS ARE THEN TRANSPOSED ANGULARLY TO A COMMON RADIAL BETWEEN THE NEXT COMMON LEVEL OBSERVATION AND THE VORTEX CENTER AT THE NEXT OBSERVATION TIME. WIND DIRECTION AND, THEREFORE, THE U (EAST-WEST) AND V (NORTH-SOUTH) COMPONENTS ARE ADJUSTED FOR THIS TRANSPOSITION. AVERAGE AND MAXIMUM OBSERVED WIND SPEEDS ARE THEN COMPUTED BETWEEN OBSERVATIONS WITH SLP OR 700MB HEIGHT INFORMATION AS LONG AS ONLY A MAXIMUM OF ONE INTERMEDIATE WIND WITHOUT PRESSURE INFORMATION OCCURS BETWEEN. FOR BOTH FLIGHT LEVEL AND SURFACE LEVEL, A PRESSURE GRADIENT IS COMPUTED AND ASSIGNED TO THE MIDPOINT DISTANCE BETWEEN OBSERVATIONS ALONG THE COMMON RADIAL. FACTORS ARE COMPUTED WHICH RELATE THE AVERAGE WIND TO THE PRESSURE/HEIGHT GRADIENT AT FLIGHT LEVEL AND AT THE SURFACE. THE MAXIMUM WIND BETWEEN OBSERVATIONS IS ALSO RELATED TO THE SAME. OUTPUT FILE NUMBER 1 IS CREATED CONTAINING THE INPUT DATA WITH TIME CONVERTED TO CONTINUOUS MINUTE FORMAT, WIND VELOCITIES WITH SYSTEM MOTION SUBTRACTED, AND WITH SLP EXTRAPOLATED WHEN NECESSARY. OUTPUT FILE NUMBER 2 CONTAINS DISTANCES TO THE MIDPOINT BETWEEN OBSERVATIONS AND THE CORRESPONDING WIND/PRESSURE FACTORS FOR THAT POINT. THE RADIUS OF STORM SIZE IS ESTIMATED BY DETERMINING A VALUE FOR THE OUTERMOST CLOSED ISOBAR AND THEN USING AN ANALYTIC MODEL TO DETERMINE ITS RADIUS. OUTPUT FILE NUMBER 3 IS CREATED CONTAINING THIS RADIUS PLUS THE ENVIRONMENTAL VALUES USED TO DETERMINE THIS RADIUS.

VARIABLE LIST************

LFLG - INDICATES CONSECUTIVE OBS WITH OR WITHOUT PRESSURE DATA
DIFTIM - TIME DIFFERENCE BETWEEN FIX AND OBSERVATION
CLAT - FLIGHT LEVEL CENTER LATITUDE AT OBSERVATION TIME
CLON - FLIGHT LEVEL CENTER LONGITUDE AT OBSERVATION TIME
SFCLAT - SURFACE CENTER LATITUDE AT OBS TIME
SFCLON - SURFACE CENTER LONGITUDE AT OBS TIME
DISLLA(I) - LATITUDE DISTANCE OF OBS(K,I) TO FLIGHT LEVEL CENTER AT TIME(K,I)
DISLLO(I) - LONGITUDE DISTANCE OF OBS(K,I) TO FLIGHT LEVEL CENTER AT TIME(K,I)
DISSLA(I) - LATITUDE DISTANCE OF OBS(K,I) TO SURFACE CENTER AT TIME(K,I)
DISSLO(I) - LONGITUDE DISTANCE OF OBS(K,I) TO SURFACE CENTER AT TIME(K,I)
C1 - CONSTANT FOR DEGREE/RADIAN RELATION
DISTL1 - DISTANCE OF OBS(K,I) TO FLIGHT LEVEL CENTER (DEG LAT)
DISTS1 - DISTANCE OF OBS(K,I) TO SURFACE CENTER (DEG LAT)
DISTL2 - DISTANCE OF OBS(K,I-1) TO FLIGHT LEVEL CENTER (DEG LAT)
DISTS2 - DISTANCE OF OBS(K,I-1) TO SURFACE CENTER (DEG LAT)
DISTL3 - DISTANCE OF OBS(K,I-2) TO FLIGHT LEVEL CENTER (DEG LAT)
DISTS3 - DISTANCE OF OBS(K,I-2) TO SURFACE CENTER (DEG LAT)
ANGL1 - RADIAL ANGLE BETWEEN FLIGHT LEVEL CENTER AND OBS(K,I)
ANGL2 - RADIAL ANGLE BETWEEN FLIGHT LEVEL CENTER AND OBS(K,I-1)
ANGS1 - RADIAL ANGLE BETWEEN SURFACE CENTER AND OBS(K,I)
ANGS2 - RADIAL ANGLE BETWEEN SURFACE CENTER AND OBS(K,I-1)
FLANG3 - FLIGHT LEVEL WIND DIRECTION ANGLE FOR OBS(K,I-2)
FLANG2 - FLIGHT LEVEL WIND DIRECTION ANGLE FOR OBS(K,I-1)
FLANG1 - FLIGHT LEVEL WIND DIRECTION ANGLE FOR OBS(K,I)
SLANG3 - SURFACE WIND DIRECTION ANGLE FOR OBS(K,I-2)
SLANG2 - SURFACE WIND DIRECTION ANGLE FOR OBS(K,I-1)
SLANG1 - SURFACE WIND DIRECTION ANGLE FOR OBS(K,I)
K1 - CONSTANT TO SEPARATE DIRECTION FROM SPEED DATA
K2 - CONSTANT TO DETERMINE WIND DIRECTION ANGLE WITHIN 10 DEGREES
LCKLAT - FLIGHT LEVEL CENTER V VELOCITY COMPONENT (KTS)

LCKLON - FLIGHT LEVEL CENTER U VELOCITY COMPONENT (KTS)
C2 - CONSTANT TO CONVERT FROM (DEG LAT)/MIN TO KNOTS
SCKLAT - SURFACE CENTER V VELOCITY COMPONENT (KTS)
SCKLON - SURFACE CENTER U VELOCITY COMPONENT (KTS)
FLVEL1 - FLIGHT LEVEL WIND SPEED FOR OBS(K,I)
FLVEL2 - FLIGHT LEVEL WIND SPEED FOR OBS(K,I-1)
FLVEL3 - FLIGHT LEVEL WIND SPEED FOR OBS(K,I-2)
FUVEL1 - FLIGHT LEVEL WIND U COMPONENT FOR OBS(K,I)
FUVEL2 - FLIGHT LEVEL WIND U COMPONENT FOR OBS(K,I-1)
FUVEL3 - FLIGHT LEVEL WIND U COMPONENT FOR OBS(K,I-2)
FVVEL1 - FLIGHT LEVEL WIND V COMPONENT FOR OBS(K,I)
FVVEL2 - FLIGHT LEVEL WIND V COMPONENT FOR OBS(K,I-1)
FVVEL3 - FLIGHT LEVEL WIND V COMPONENT FOR OBS(K,I-2)
SFVEL1 - SURFACE WIND SPEED FOR OBS(K,I)
SFVEL2 - SURFACE WIND SPEED FOR OBS(K,I-1)
SFVEL3 - SURFACE WIND SPEED FOR OBS(K,I-2)
SUVEL1 - SURFACE WIND U COMPONENT FOR OBS(K,I)
SUVEL2 - SURFACE WIND U COMPONENT FOR OBS(K,I-1)
SUVEL3 - SURFACE WIND U COMPONENT FOR OBS(K,I-2)
SVVEL1 - SURFACE WIND V COMPONENT FOR OBS(K,I)
SVVEL2 - SURFACE WIND V COMPONENT FOR OBS(K,I-1)
SVVEL3 - SURFACE WIND V COMPONENT FOR OBS(K,I-2)
LANDIF - ANGULAR DIFFERENCE BETWEEN ANGL1 AND ANGL2
SANDIF - ANGULAR DIFFERENCE BETWEEN ANGS1 AND ANGS2
A - COUNTER OF MISSING FLIGHT LEVEL WINDS
K3 - CODE FOR MISSING WIND
IFLG - FLAG FOR MID POINT WIND VERIFICATION
FLUVEL - AVERAGE FLIGHT LEVEL WIND U VELOCITY COMPONENT
FLVVEL - AVERAGE FLIGHT LEVEL WIND V VELOCITY COMPONENT
FLMAX - MAX FLIGHT LEVEL WIND SPEED BETWEEN OBS WITH PRESSURE DATA
B - COUNTER OF MISSING SURFACE WINDS
SFUVEL - AVERAGE SURFACE WIND U VELOCITY COMPONENT
SFVVEL - AVERAGE SURFACE WIND V VELOCITY COMPONENT
SFMAX - MAXIMUM SURFACE WIND SPEED BETWEEN OBS WITH PRESSURE DATA
IFLDIR - AVERAGE FLIGHT LEVEL WIND DIRECTION ANGLE
ISFDIR - AVERAGE SURFACE WIND DIRECTION ANGLE
FLVEL - AVERAGE FLIGHT LEVEL WIND SPEED
SFVEL - AVERAGE SURFACE WIND SPEED
DISTL - AVERAGE DISTANCE OF OBS TO FLIGHT LEVEL CENTER
DISTS - AVERAGE DISTANCE OF OBS TO SURFACE CENTER
C3 - CONSTANT OF CONVERSION FROM DEG LAT TO NAUTICAL MILE
IPSCHG - SURFACE PRESSURE CHANGE (MB) BETWEEN OBS WITH PRESSURE DATA
IPLCHG - FLIGHT LEVEL PRESSURE HEIGHT CHANGE (METERS) BETWEEN OBS WITH PRESSURE DATA
GRADIL - GRADIENT DISTANCE AT FLIGHT LEVEL BETWEEN OBSERVATIONS ALONG A COMMON RADIAL
GRADIS - GRADIENT DISTANCE AT SURFACE BETWEEN OBS ALONG A COMMON RADIAL
PGRADL - PRESSURE GRADIENT AT FLIGHT LEVEL BETWEEN OBS ALONG A COMMON RADIAL
PGRADS - PRESSURE GRADIENT AT SURFACE BETWEEN OBS ALONG A COMMON RADIAL
IFLW3 - TEMPORARY FLIGHT LEVEL WIND
IFLW2 - TEMPORARY FLIGHT LEVEL WIND (OR INTERMEDIATE WIND)
ISLP1 - TEMPORARY SLP
ISLP2 - TEMPORARY SLP
IHSS1 - TEMPORARY HSS
IHSS2 - TEMPORARY HSS
IPN - ENVIRONMENTAL SEA LEVEL PRESSURE
IPE - TROPICAL CYCLONE SEA LEVEL PRESSURE LIMIT
PWL - 700MB FLIGHT LEVEL WIND/PRESSURE HEIGHT GRADIENT FACTOR USING AVERAGE WIND
PWLM - 700MB FLIGHT LEVEL WIND/PRESSURE HEIGHT GRADIENT FACTOR USING MAXIMUM WIND
PWSS - SURFACE WIND/PRESSURE GRADIENT FACTOR USING AVERAGE WIND
PWSSM - SURFACE WIND/PRESSURE GRADIENT FACTOR USING MAXIMUM WIND
PWLS - SURFACE WIND/700MB PRESSURE HEIGHT GRADIENT FACTOR USING

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      AVERAGE WIND
      PWLSM - SURFACE WIND/700MB PRESSURE HEIGHT GRADIENT FACTOR USING
      MAXIMUM WIND
      PWSL - LOW LEVEL WIND/SURFACE PRESSURE GRADIENT FACTOR USING
      AVERAGE WIND
      PWSLM - LOW LEVEL WIND/SURFACE PRESSURE GRADIENT FACTOR USING
      MAXIMUM WIND
      ISLPM - UPPER LIMIT OF SLP FOR RADIAL SIZE COMPUTATION
      DISTM - DISTANCE OF LAST OBS IN RADIAL SIZE COMPUTATION
      DISTN - OUTER LIMIT DISTANCE FOR MINIMUM WIND RADIAL SIZE COMP
      DISTO - INNER LIMIT DISTANCE FOR RADIAL SIZE COMPUTATION
      DISTP - INNER LIMIT DISTANCE FOR MAXIMUM WIND RADIAL SIZE COMP
      RS - RADIAL SIZE
      BB - PARAMETER FOR LOG PRESSURE PROFILE
      N1 - NUMBER OF PRESSURE GRADIENT COMPUTATIONS
      IPED - CORRECTION TO IPE FOR DIURNAL ATMOSPHERIC TIDE
      CC - TIME DIFFERENCE BETWEEN OBS AND NEXT SURFACE FIX
      DD - TIME DIFFERENCE BETWEEN SURROUNDING SURFACE FIXES
      RAT - RATIO OF TIME BETWEEN FIXES
      ISCSLP - INTERPOLATED VALUE OF CURRENT CENTRAL SLP
      EE - DIFFERENCE BETWEEN ENVIRONMENTAL AND CENTRAL SLP
      FF - DIFFERENCE BETWEEN OBSERVED AND CENTRAL SLP
      AA - PARAMETER FOR LOG PRESSURE PROFILE
      GG - DIFFERENCE BETWEEN OUTER LIMIT ISOBAR AND CENTRAL SLP

      DO13 K=1,NN
        WRITE(17,10)NUM(K),N(K)
        WRITE(18,10)NUM(K),N(K)
10      FORMAT(1X,I7,7X,I2)
        IPE=1008
        ISLPM=2000
        DISTM=0.
        DISTN=1000.
        DISTO=0.
        DISTP=0.
        RS=0.
        BB=0.
        N1=0
        DO12 I=1,N(K)
          IF(LCMIN(J).LT.TIME(K,I).AND.J.LT.JJ)J=J+1
          ISLP1=SLP(K,I)
          IHSS1=HSS(K,I)
          IF(CODE(K,I).EQ.11)
          KLL=KLL+1
          IF(KLL.EQ.2.AND.SLP(K,I-1).EQ.0)KLL=1
          DIFTIM=LCMIN(J)-TIME(K,I)
          CLAT=LCLAT(J)-LCVLAT(J)*DIFTIM
          CLON=LCLON(J)-LCVLON(J)*DIFTIM
          DIFTIM=SCMIN(J)-TIME(K,I)
          SFCLAT=SCLAT(J)-SCVLAT(J)*DIFTIM
          SFCLON=SCLON(J)-SCVLON(J)*DIFTIM
          DISLLA(I)=LAT(K,I)-CLAT
          DISLLO(I)=(LON(K,I)-CLON)*COS(LAT(K,I)/C1)
          DISSLA(I)=LAT(K,I)-SFCLAT
          DISSLO(I)=(LON(K,I)-SFCLON)*COS(LAT(K,I)/C1)
          DISTL1=SQRT(DISLLA(I)**2+DISLLO(I)**2)
          DISTS1=SQRT(DISSLA(I)**2+DISSLO(I)**2)
          LCKLAT=LCVLAT(J)*C2
          LCKLON=LCVLON(J)*(COS(LCLAT(J)/C1))*C2
          SCKLAT=SCVLAT(J)*C2
          SCKLON=SCVLON(J)*(COS(SCLAT(J)/C1))*C2
          IF(KLL.EQ.1)
          LFLG=0
          KHH=0
          ANGL1=ATAN2(DISLLO(I),DISLLA(I))*C1
          IF(ANGL1.LE.0.)ANGL1=360.+ANGL1
          ANGS1=ATAN2(DISSLO(I),DISSLA(I))*C1
          IF(ANGS1.LE.0.)ANGS1=360.+ANGS1
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FLANG1=(FLW(K,I)/K1)*K2
SLANG1=(SFW(K,I)/K1)*K2
FLVEL1=FLOAT(FLW(K,I)-(FLW(K,I)/K1)*K1)
CALL COMP(FLVEL1,FLANG1,C1,LCKLAT,LCKLON,FUVEL1,FVVEL1)
SFVEL1=FLOAT(SFW(K,I)-(SFW(K,I)/K1)*K1)
CALL COMP(SFVEL1,SLANG1,C1,SCKLAT,SCKLON,SUVEL1,SVVEL1)
GO TO 34
END IF
IF(ISLP1.LT.800)
IF(SLP(K,I+1).LT.800.OR.SLP(K,I-1).LT.800)
FLANG1=900
SLANG1=900
GO TO 34
END IF
LFLG=1
END IF
IF(SLP(K,I-1).LT.800.AND.LFLG.EQ.0)
FLANG1=900
SLANG1=900
GO TO 34
END IF
IF(LFLG.EQ.2)
DISTL3=DISTL2
DISTS3=DISTS2
END IF
DISTL2=SQRT(DISLLA(I-1)**2+DISLLO(I-1)**2)
DISTS2=SQRT(DISSLA(I-1)**2+DISSLO(I-1)**2)
IF(DISTL2.NE.0.)
ANGL1=ATAN2(DISLLO(I),DISLLA(I))*C1
IF(ANGL1.LE.0.)ANGL1=360.+ANGL1
ANGL2=ATAN2(DISLLO(I-1),DISLLA(I-1))*C1
IF(ANGL2.LE.0.)ANGL2=360.+ANGL2
END IF
IF(DISTS2.NE.0.)
ANGS1=ATAN2(DISSLO(I),DISSLA(I))*C1
IF(ANGS1.LE.0.)ANGS1=360.+ANGS1
ANGS2=ATAN2(DISSLO(I-1),DISSLA(I-1))*C1
IF(ANGS2.LE.0.)ANGS2=360.+ANGS2
END IF
IF(LFLG.EQ.2)
FLANG3=FLANG2
SLANG3=SLANG2
END IF
FLANG1=(FLW(K,I)/K1)*K2
SLANG1=(SFW(K,I)/K1)*K2
FLANG2=(FLW(K,I-1)/K1)*K2
SLANG2=(SFW(K,I-1)/K1)*K2
FLVEL1=FLOAT(FLW(K,I)-(FLW(K,I)/K1)*K1)
CALL COMP(FLVEL1,FLANG1,C1,LCKLAT,LCKLON,FUVEL1,FVVEL1)
FLVEL2=FLOAT(FLW(K,I-1)-(FLW(K,I-1)/K1)*K1)
CALL COMP(FLVEL2,FLANG2,C1,LCKLAT,LCKLON,FUVEL2,FVVEL2)
SFVEL1=FLOAT(SFW(K,I)-(SFW(K,I)/K1)*K1)
CALL COMP(SFVEL1,SLANG1,C1,SCKLAT,SCKLON,SUVEL1,SVVEL1)
SFVEL2=FLOAT(SFW(K,I-1)-(SFW(K,I-1)/K1)*K1)
CALL COMP(SFVEL2,SLANG2,C1,SCKLAT,SCKLON,SUVEL2,SVVEL2)
IF(LFLG.EQ.2)
FLVEL3=FLOAT(FLW(K,I-2)-(FLW(K,I-2)/K1)*K1)
CALL COMP(FLVEL3,FLANG3,C1,LCKLAT,LCKLON,FUVEL3,FVVEL3)
SFVEL3=FLOAT(SFW(K,I-2)-(SFW(K,I-2)/K1)*K1)
CALL COMP(SFVEL3,SLANG3,C1,SCKLAT,SCKLON,SUVEL3,SVVEL3)
END IF
IF(DISTL2.NE.0.)
LANDIF=INT(ANGL1-ANGL2)
FLANG2=FLANG2+LANDIF
IF(FLANG2.GT.360)FLANG2=FLANG2-360
IF(FLANG2.LE.0)FLANG2=360+FLANG2
END IF
IF(DISTS2.NE.0.)
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      SANDIF=INT(ANGS1-ANGS2)
      SLANG2=SLANG2+SANDIF
      IF(SLANG2.GT.360)SLANG2=SLANG2-360
      IF(SLANG2.LE.0)SLANG2=360+SLANG2
      END IF
      IF(LFLG.EQ.2)
      FLANG3=FLANG3+LANDIF
      SLANG3=SLANG3+LANDIF
      IF(FLANG3.GT.360)FLANG3=FLANG3-360
      IF(FLANG3.LE.0)FLANG3=360+FLANG3
      IF(SLANG3.GT.360)SLANG3=SLANG3-360
      IF(SLANG3.LE.0)SLANG3=360+SLANG3
      A=0.
      IF(FLW(K,I-2).EQ.K3)
      A=A+1.
      FUVEL3=0.
      FVVEL3=0.
      END IF
      CALL MID(DISTL1,DISTL2,DISTL3,IFLG,FUVEL2,FVVEL2,A)
      IF(IFLG-1)49,50,49
49    IF(FLW(K,I-1).EQ.K3)
      A=A+1.
      FUVEL2=0.
      FVVEL2=0.
      END IF
50    IF(FLW(K,I).EQ.K3)
      A=A+1.
      FUVEL1=0.
      FVVEL1=0.
      END IF
      IF(A.EQ.3.)
      FLUVEL=500.
      FLVVEL=500.
      ELSE
      FLUVEL=(FUVEL1+FUVEL2+FUVEL3)/(3.0-A)
      FLVVEL=(FVVEL1+FVVEL2+FVVEL3)/(3.0-A)
      END IF
      B=0.
      IF(SFW(K,I-2).EQ.K3)
      B=B+1.
      SUVEL3=0.
      SVVEL3=0.
      END IF
      CALL MID(DISTS1,DISTS2,DISTS3,IFLG,SUVEL2,SVVEL2,B)
      IF(IFLG-1)48,51,48
48    IF(SFW(K,I-1).EQ.K3)
      B=B+1.
      SUVEL2=0.
      SVVEL2=0.
      END IF
51    IF(SFW(K,I).EQ.K3)
      B=B+1.
      SUVEL1=0.
      SVVEL1=0.
      END IF
      IF(B.EQ.3.)
      SFUVEL=500.
      SFVVEL=500.
      ELSE
      SFUVEL=(SUVEL1+SUVEL2+SUVEL3)/(3.0-B)
      SFVVEL=(SVVEL1+SVVEL2+SVVEL3)/(3.0-B)
      END IF
      ELSE
      A=0.
      IF(FLW(K,I-1).EQ.K3)
      A=A+1.
      FUVEL2=0.
      FVVEL2=0.
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```
      END IF
      IF(FLW(K,I).EQ.K3)
      A=A+1.
      FUVEL1=0.
      FVVEL1=0.
      END IF
      IF(A.EQ.2.)
      FLUVEL=500.
      FLVVEL=500.
      ELSE
      FLUVEL=(FUVEL1+FUVEL2)/(2.0-A)
      FLVVEL=(FVVEL1+FVVEL2)/(2.0-A)
      END IF
      FUVEL3=0.
      FVVEL3=0.
      B=0.
      IF(SFW(K,I-1).EQ.K3)
      B=B+1.
      SUVEL2=0.
      SVVEL2=0.
      END IF
      IF(SFW(K,I).EQ.K3)
      B=B+1.
      SUVEL1=0
      SVVEL1=0.
      END IF
      IF(B.EQ.2.)
      SFUVEL=500.
      SFVVEL=500.
      ELSE
      SFUVEL=(SUVEL1+SUVEL2)/(2.0-B)
      SFVVEL=(SVVEL1+SVVEL2)/(2.0-B)
      END IF
      SUVEL3=0.
      SVVEL3=0.
      END IF
      CALL MAXI(FUVEL1,FUVEL2,FUVEL3,FVVEL1,FVVEL2,FVVEL3,FLMAX)
      CALL MAXI(SUVEL1,SUVEL2,SUVEL3,SVVEL1,SVVEL2,SVVEL3,SFMAX)
      IFLDIR=INT(ATAN2(FLUVEL,FLVVEL)*C1-180.)
      ISFDIR=INT(ATAN2(SFUVEL,SFVVEL)*C1-180.)
      IF(IFLDIR.LE.0)IFLDIR=360+IFLDIR
      IF(ISFDIR.LE.0)ISFDIR=360+ISFDIR
      FLVEL=SQRT(FLUVEL**2+FLVVEL**2)
      SFVEL=SQRT(SFUVEL**2+SFVVEL**2)
      IF(LFLG.EQ.2)
      LFLG=0
      ISLP2=SLP(K,I-2)
      DISTL=((DISTL3+DISTL1)/2.)*C3
      DISTS=((DISTS3+DISTS1)/2.)*C3
      IPSCHG=ISLP2-ISLP1
      IF(IPSCHG)47,34,47
47    GRADIL=(DISTL3-DISTL1)*C3
      GRADIS=(DISTS3-DISTS1)*C3
      IF(GRADIL.EQ.0.)
      PWSL=-999
      PWSLM=-999.
      ELSE
      PGRADL=IPSCHG/GRADIL
      PWSL=FLVEL/PGRADL
      PWSLM=FLMAX/PGRADL
      IF(FLVEL.GT.500.)
      PWSL=-999.
      PWSLM=-999.
      END IF
      END IF
      IF(GRADIS.EQ.0.)
      PWSS=-999.
      PWSSM=-999.
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      GO TO 129
      ELSE
      PGRADS=IPSCHG/GRADIS
      PWSS=SFVEL/PGRADS
      PWSSM=SFMAX/PGRADS
      IF(SFVEL.GT.500.)
      PWSS=-999.
      PWSSM=-999.
      END IF
      END IF
      GO TO 129
      ELSE
      IF(LFLG.EQ.1)
      LFLG=2
      GO TO 34
      ELSE
      ISLP2=SLP(K,I-1)
      DISTL=((DISTL2+DISTL1)/2.)*C3
      DISTS=((DISTS2+DISTS1)/2.)*C3
      IPSCHG=ISLP2-ISLP1
      IF(IPSCHG)44,34,44
44    GRADIL=(DISTL2-DISTL1)*C3
      GRADIS=(DISTS2-DISTS1)*C3
      IF(GRADIL.EQ.0.)
      PWSL=-999.
      PWSLM=-999.
      ELSE
      PGRADL=IPSCHG/GRADIL
      PWSL=FLVEL/PGRADL
      PWSLM=FLMAX/PGRADL
      IF(FLVEL.GT.500.)
      PWSL=-999.
      PWSLM=-999.
      END IF
      END IF
      IF(GRADIS.EQ.0.)
      PWSS=-999.
      PWSSM=-999.
      GO TO 129
      ELSE
      PGRADS=IPSCHG/GRADIS
      PWSS=SFVEL/PGRADS
      PWSSM=SFMAX/PGRADS
      IF(SFVEL.GT.500.)
      PWSS=-999.
      PWSSM=-999
      END IF
      END IF
      GO TO 129
      END IF
      END IF
      ELSE
      IF(CODE(K,I).EQ.21)
      BB=.5
      KLL=KLL+1
      IF(KLL.EQ.2.AND.SLP(K,I-1).EQ.0)KLL=1
      DISSLA(I)=0
      DISSLO(I)=0
      DISLLA(I)=0
      DISLLO(I)=0.
      IF(KLL.EQ.1)
      FLANG1=900
      SLANG1=900
      LFLG=0
      KHH=0
      GO TO 34
      END IF
      IF(ISLP1.LT.800)
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      FLANG1=900
      SLANG1=900
      GO TO 34
      END IF
      IF(SLP(K,I-1).LT.800.AND.LFLG.EQ.0)
      FLANG1=900
      SLANG1=900
      GO TO 34
      END IF
      DISTL1=0.
      DISTS1=0.
      FLANG1=(FLW(K,I)/K1)*K2
      SLANG1=(SFW(K,I)/K1)*K2
      IF(LFLG.EQ.2)
      DISTS3=DISTS2
      SLANG3=SLANG2
      END IF
      DISTS2=SQRT(DISSLA(I-1)**2+DISSLO(I-1)**2)
      SLANG2=(SFW(K,I-1)/K1)*K2
      SCKLAT=SCVLAT(J)*C2
      SCKLON=SCVLON(J)*(COS(SCLAT(J)/C1))*C2
      SFVEL2=FLOAT(SFW(K,I-1)-(SFW(K,I-1)/K1)*K1)
      CALL COMP(SFVEL2,SLANG2,C1,SCKLAT,SCKLON,SUVEL2,SVVEL2)
      B=0.
      IF(LFLG.EQ.2)
      SFVEL3=FLOAT(SFW(K,I-2)-(SFW(K,I-2)/K1)*K1)
      CALL COMP(SFVEL3,SLANG3,C1,SCKLAT,SCKLON,SUVEL3,SVVEL3)
      IF(SFW(K,I-2).EQ.K3)
      B=B+1.
      SUVEL3=0
      SVVEL3=0.
      END IF
      CALL MID(DISTS1,DISTS2,DISTS3,IFLG,SUVEL2,SVVEL2,B)
      IF(IFLG-1)45,53,45
45    IF(SFW(K,I-1).EQ.K3)
      B=B+1.
      SUVEL2=0.
      SVVEL2=0.
      END IF
53    IF(B.EQ.2.)
      SFUVEL=500.
      SFVVEL=500.
      ELSE
      SFUVEL=(SUVEL2+SUVEL3)/(2.0-B)
      SFVVEL=(SVVEL2+SVVEL3)/(2.0-B)
      SUVEL1=0.
      SVVEL1=0.
      END IF
      ELSE
      IF(SFW(K,I-1).NE.K3)
      SFUVEL=SUVEL2
      SFVVEL=SVVEL2
      SUVEL1=0.
      SVVEL1=0.
      SUVEL3=0.
      SVVEL3=0.
      ELSE
      SFUVEL=500
      SFVVEL=500.
      END IF
      END IF
      CALL MAXI(SUVEL1,SUVEL2,SUVEL3,SVVEL1,SVVEL2,SVVEL3,SFMAX)
      IFLDIR=-1
      ISFDIR=INT(ATAN2(SFUVEL,SFVVEL)*C1-180.)
      IF(ISFDIR.LE.0)ISFDIR=360+ISFDIR
      FLVEL=999.
      SFVEL=SQRT(SFUVEL**2+SFVVEL**2)
      IF(LFLG.EQ.2)
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          ISLP2=SLP(K,I-2)
          DISTS=(DISTS3/2.)*C3
          IPSCHG=ISLP2-ISLP1
          IF(IPSCHG)140,34,140
140       GRADIS=DISTS3*C3
          PWSL=-999.
          PWSLM=-999.
          IF(GRADIS)143,34,143
143       PGRADS=IPSCHG/GRADIS
          CALL BEE(PGRADS,BB)
          PWSS=SFVEL/PGRADS
          PWSSM=SFMAX/PGRADS
          IF(SFVEL.GT.500.)
          PWSS=-999.
          PWSSM=-999..
          END IF
          GO TO 129
          ELSE
          ISLP2=SLP(K,I-1)
          DISTS=(DISTS2/2.)*C3
          IPSCHG=ISLP2-ISLP1
          IF(IPSCHG)144,34,144
144       GRADIS=DISTS2*C3
          PWSL=-999.
          PWSLM=-999.
          IF(GRADIS)147,34,147
147       PGRADS=IPSCHG/GRADIS
          CALL BEE(PGRADS,BB)
          PWSS=SFVEL/PGRADS
          PWSSM=SFMAX/PGRADS
          IF(SFVEL.GT.500.)
          PWSS=-999.
          PWSSM=-999.
          END IF
          GO TO 129
          END IF
          ELSE
          IF(CODE(K,I).EQ.41)
          KLL=KLL+1
          BB=.5
          IF(KLL.EQ.2.AND.SLP(K,I-1).EQ.0)KLL=1
          DISLLA(I)=0.
          DISLLO(I)=0.
          DISSLA(I)=0.
          DISSLO(I)=0.
          IF(KLL.EQ.1)
          FLANG1=900
          SLANG1=900
          LFLG=0
          KHH=0
          GO TO 34
          END IF
          IF(ISLP1.LT 800)
          FLANG1=900
          SLANG1=900
          LFLG=0
          GO TO 34
          END IF
          IF(CODE(K,I-1).NE.21)
          IF(SLP(K,I-1).LT.800.AND.LFLG.EQ.0)
          FLANG1=900
          SLANG1=900
          GO TO 34
          END IF
          FLANG1=(FLW(K,I)/K1)*K2
          SLANG1=(SFW(K,I)/K1)*K2
          IF(LFLG.EQ.2)
          DISTS3=DISTS2
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```
      SLANG3=SLANG2
      SUVEL3=SUVEL2
      SVVEL3=SVVEL2
      END IF
      DISTS2=DISTS1
      DISTS1=0.
      SLANG2=SLANG1
      SUVEL2=SUVEL1
      SVVEL2=SVVEL1
      B=0.
      IF(LFLG.EQ.2)
      IF(SFW(K,I-2).EQ.K3)
      B=B+1.
      SUVEL3=0.
      SVVEL3=0.
      END IF
      CALL MID(DISTS1,DISTS2,DISTS3,IFLG,SUVEL2,SVVEL2,B)
      IF(IFLG-1)205,206,205
205   IF(SFW(K,I-1).EQ.K3)
      B=B+1.
      SUVEL2=0.
      SVVEL2=0.
      END IF
206   IF(B.EQ.2.)
      SFUVEL=500.
      SFVVEL=500.
      ELSE
      SFUVEL=(SUVEL2+SUVEL3)/(2.-B)
      SFVVEL=(SVVEL2+SVVEL3)/(2.-B)
      SUVEL1=0.
      SVVEL1=0.
      END IF
      ELSE
      IF(SFW(K,I-1).NE.K3)
      SFUVEL=SUVEL2
      SFVVEL=SVVEL2
      SUVEL1=0.
      SVVEL1=0.
      SUVEL3=0.
      SVVEL3=0.
      ELSE
      SFUVEL=500.
      SFVVEL=500.
      END IF
      END IF
      CALL MAXI(SUVEL1,SUVEL2,SUVEL3,SVVEL1,SVVEL2,SVVEL3,SFMAX)
      ISFDIR=INT(ATAN2(SFUVEL,SFVVEL)*C1-180.)
      IF(ISFDIR.LE.0)ISFDIR=360+ISFDIR
      SFVEL=SQRT(SFUVEL**2+SFVVEL**2)
      IF(SFVEL.GT.500.)SFVEL=999.
      ELSE
      DISTS1=0.
      IF(SLP(K,I-2).LT.800.AND.LFLG.EQ.0)GO TO 34
      END IF
      IF(LFLG.EQ.2)
      DISTL3=DISTL2
      FLANG3=FLANG2
      END IF
      DISTL1=0.
      FLANG2=FLANG1
      IF(CODE(K,I-1).EQ.21)
      DISTL2=SQRT(DISLLA(I-2)**2+DISLLO(I-2)**2)
      IFLW3=FLW(K,I-3)
      IFLW2=FLW(K,I-2)
      ELSE
      DISTL2=SQRT(DISLLA(I-1)**2+DISLLO(I-1)**2)
      IFLW3=FLW(K,I-2)
      IFLW2=FLW(K,I-1)
```

```
      END IF
      IF(LFLG.EQ.2)
      FUVEL3=FUVEL2
      FVVEL3=FVVEL2
      END IF
      FUVEL2=FUVEL1
      FVVEL2=FVVEL1
      A=0.
      IF(LFLG.EQ.2)
      IF(IFLW3.EQ.K3)
      A=A+1.
      FUVEL3=0.
      FVVEL3=0.
      END IF
      CALL MID(DISTL1,DISTL2,DISTL3,IFLG,FUVEL2,FVVEL2,A)
      IF(IFLG-1)251,252,251
251   IF(IFLW2.EQ.K3)
      A=A+1.
      FUVEL2=0.
      FVVEL2=0.
      END IF
252   IF(A.EQ.2.)
      FLUVEL=500.
      FLVVEL=500.
      ELSE
      FLUVEL=(FUVEL2+FUVEL3)/(2.0-A)
      FLVVEL=(FVVEL2+FVVEL3)/(2.0-A)
      FUVEL1=0.
      FVVEL1=0.
      END IF
      ELSE
      IF(IFLW2.NE.K3)
      FLUVEL=FUVEL2
      FLVVEL=FVVEL2
      FUVEL1=0.
      FVVEL1=0.
      FUVEL3=0.
      FVVEL3=0.
      ELSE
      FLUVEL=500.
      FLVVEL=500.
      END IF
      END IF
      CALL MAXI(FUVEL1,FUVEL2,FUVEL3,FVVEL1,FVVEL2,FVVEL3,FLMAX)
      IFLDIR=INT(ATAN2(FLUVEL,FLVVEL)*C1-180.)
      IF(CODE(K,I-1).EQ.21)
      SFVEL=999.
      ISFDIR=-1
      END IF
      IF(IFLDIR.LE.0)IFLDIR=360+IFLDIR
      FLVEL=SQRT(FLUVEL**2+FLVVEL**2)
      IF(LFLG.EQ.2)
      LFLG=0
      DISTL=(DISTL3/2.)*C3
      IF(CODE(K,I-1).EQ.21)
      ISLP2=SLP(K,I-3)
      ELSE
      ISLP2=SLP(K,I-2)
      END IF
      IPSCHG=ISLP2-ISLP1
      IF(IPSCHG)289,34,289
289   GRADIL=DISTL3*C3
      IF(GRADIL)288,34,288
288   PGRADL=IPSCHG/GRADIL
      PWSL=FLVEL/PGRADL
      PWSLM=FLMAX/PGRADL
      IF(FLVEL.GT.500.)
      PWSL=-999.
```

```
      PWSLM=-999.
      END IF
      IF(CODE(K,I-1).EQ.21)
      PWSS=-999.
      PWSSM=-999.
      PGRADS=-9.9999
      ELSE
      PGRADS=PGRADL
      CALL BEE(PGRADS,BB)
      IF(SFVEL.EQ.999.)
      PWSS=-999.
      PWSSM=-999.
      ELSE
      PWSS=SFVEL/PGRADS
      PWSSM=SFMAX/PGRADS
      END IF
      END IF
      GO TO 129
      ELSE
      DISTL=(DISTL2/2.)*C3
      IF(CODE(K,I-1).EQ.21)
      ISLP2=SLP(K,I-2)
      ELSE
      ISLP2=SLP(K,I-1)
      END IF
      IPSCHG=ISLP2-ISLP1
      IF(IPSCHG)244,34,244
244   GRADIL=DISTL2*C3
      IF(GRADIL)240,34,240
240   PGRADL=IPSCHG/GRADIL
      PWSL=FLVEL/PGRADL
      PWSLM=FLMAX/PGRADL
      IF(FLVEL.GT.500.)
      PWSL=-999.
      PWSLM=-999.
      END IF
      IF(CODE(K,I-1).EQ.21)
      PWSS=-999.
      PWSSM=-999.
      PGRADS=-9.9999
      ELSE
      PGRADS=PGRADL
      CALL BEE(PGRADS,BB)
      IF(SFVEL.EQ.999.)
      PWSS=-999.
      PWSSM=-999.
      GO TO 129
      ELSE
      PWSS=SFVEL/PGRADS
      PWSSM=SFMAX/PGRADS
      END IF
      END IF
      END IF
      GO TO 129
      END IF
      END IF
      END IF
      GO TO 110
129   N1=N1+1
      PWL=-999.
      PWLM=-999.
      PWLS=-999.
      PWLSM=-999.
      WRITE(18,123)DISTL,DISTS,PWL,PWSS,PWLM,PWSSM,PWLS,PWLSM,
      PWSL,PWSLM
123   FORMAT(2(1X,F4.0),8(1X,F6.0))
 34   WRITE(17,5)CODE(K,I),TIME(K,I),LAT(K,I),LON(K,I),FLANG1,
      FLVEL1,HSS(K,I),SLANG1,SFVEL1,SLP(K,I)
```

```
5       FORMAT(1X,I2,1X,I6,1X,F4.1,1X,F5.1,2(1X,I3,'/',F4.0,1X,I4))
        GO TO 196
110     IF(CODE(K,I).EQ.10)
        KHH=KHH+1
        IF(KHH.EQ.2.AND.HSS(K,I-1).EQ.0)KHH=1
        DIFTIM=LCMIN(J)-TIME(K,I)
        CLAT=LCLAT(J)-LCVLAT(J)*DIFTIM
        CLON=LCLON(J)-LCVLON(J)*DIFTIM
        DIFTIM=SCMIN(J)-TIME(K,I)
        SFCLAT=SCLAT(J)-SCVLAT(J)*DIFTIM
        SFCLON=SCLON(J)-SCVLON(J)*DIFTIM
        DISLLA(I)=LAT(K,I)-CLAT
        DISLLO(I)=(LON(K,I)-CLON)*COS(LAT(K,I)/C1)
        DISSLA(I)=LAT(K,I)-SFCLAT
        DISSLO(I)=(LON(K,I)-SFCLON)*COS(LAT(K,I)/C1)
        DISTL1=SQRT(DISLLA(I)**2+DISLLO(I)**2)
        DISTS1=SQRT(DISSLA(I)**2+DISSLO(I)**2)
        LCKLAT=LCVLAT(J)*C2
        LCKLON=LCVLON(J)*(COS(LCLAT(J)/C1))*C2
        SCKLAT=SCVLAT(J)*C2
        SCKLON=SCVLON(J)*(COS(SCLAT(J)/C1))*C2
        IF(KHH.EQ.1)
        KLL=0
        LFLG=0
        ANGL1=ATAN2(DISLLO(I),DISLLA(I))*C1
        IF(ANGL1.LE.0.)ANGL1=360.+ANGL1
        ANGS1=ATAN2(DISSLO(I),DISSLA(I))*C1
        IF(ANGS1.LE.0.)ANGS1=360.+ANGS1
        FLANG1=(FLW(K,I)/K1)*K2
        SLANG1=(SFW(K,I)/K1)*K2
        FLVEL1=FLOAT(FLW(K,I)-(FLW(K,I)/K1)*K1)
        CALL COMP(FLVEL1,FLANG1,C1,LCKLAT,LCKLON,FUVEL1,FVVEL1)
        SFVEL1=FLOAT(SFW(K,I)-(SFW(K,I)/K1)*K1)
        CALL COMP(SFVEL1,SLANG1,C1,SCKLAT,SCKLON,SUVEL1,SVVEL1)
        GO TO 134
        END IF
        IF(IHSS1.EQ.0)
        IF(HSS(K,I+1).EQ.0.OR.HSS(K,I-1).EQ.0)
        FLANG1=900
        SLANG1=900
        GO TO 134
        END IF
        LFLG=1
        END IF
        IF(HSS(K,I-1).EQ.0.AND.LFLG.EQ.0)
        FLANG1=900
        SLANG1=900
        GO TO 134
        END IF
        DISTL1=SQRT(DISLLA(I)**2+DISLLO(I)**2)
        DISTS1=SQRT(DISSLA(I)**2+DISSLO(I)**2)
        IF(LFLG.EQ.2)
        DISTL3=DISTL2
        DISTS3=DISTS2
        END IF
        DISTL2=SQRT(DISLLA(I-1)**2+DISLLO(I-1)**2)
        DISTS2=SQRT(DISSLA(I-1)**2+DISSLO(I-1)**2)
        IF(DISTL2.NE.0.)
        ANGL1=ATAN2(DISLLO(I),DISLLA(I))*C1
        IF(ANGL1.LE.0.)ANGL1=360.+ANGL1
        ANGL2=ATAN2(DISLLO(I-1),DISLLA(I-1))*C1
        IF(ANGL2.LE.0.)ANGL2=360.+ANGL2
        END IF
        IF(DISTS2.NE.0.)
        ANGS1=ATAN2(DISSLO(I),DISSLA(I))*C1
        IF(ANGS1.LE.0.)ANGS1=360.+ANGS1
        ANGS2=ATAN2(DISSLO(I-1),DISSLA(I-1))*C1
        IF(ANGS2.LE.0.)ANGS2=360.+ANGS2
```

```
        END IF
        IF(LFLG.EQ.2)
        FLANG3=FLANG2
        SLANG3=SLANG2
        END IF
        FLANG1=(FLW(K,I)/K1)*K2
        SLANG1=(SFW(K,I)/K1)*K2
        FLANG2=(FLW(K,I-1)/K1)*K2
        SLANG2=(SFW(K,I-1)/K1)*K2
        LCKLAT=LCVLAT(J)*C2
        LCKLON=LCVLON(J)*(COS(LCLAT(J)/C1))*C2
        SCKLAT=SCVLAT(J)*C2
        SCKLON=SCVLON(J)*(COS(SCLAT(J)/C1))*C2
        FLVEL1=FLOAT(FLW(K,I)-(FLW(K,I)/K1)*K1)
        CALL COMP(FLVEL1,FLANG1,C1,LCKLAT,LCKLON,FUVEL1,FVVEL1)
        FLVEL2=FLOAT(FLW(K,I-1)-(FLW(K,I-1)/K1)*K1)
        CALL COMP(FLVEL2,FLANG2,C1,LCKLAT,LCKLON,FUVEL2,FVVEL2)
        SFVEL1=FLOAT(SFW(K,I)-(SFW(K,I)/K1)*K1)
        CALL COMP(SFVEL1,SLANG1,C1,SCKLAT,SCKLON,SUVEL1,SVVEL1)
        SFVEL2=FLOAT(SFW(K,I-1)-(SFW(K,I-1)/K1)*K1)
        CALL COMP(SFVEL2,SLANG2,C1,SCKLAT,SCKLON,SUVEL2,SVVEL2)
        IF(LFLG.EQ.2)
        FLVEL3=FLOAT(FLW(K,I-2)-(FLW(K,I-2)/K1)*K1)
        CALL COMP(FLVEL3,FLANG3,C1,LCKLAT,LCKLON,FUVEL3,FVVEL3)
        SFVEL3=FLOAT(SFW(K,I-2)-(SFW(K,I-2)/K1)*K1)
        CALL COMP(SFVEL3,SLANG3,C1,SCKLAT,SCKLON,SUVEL3,SVVEL3)
        END IF
        IF(DISTL2.NE.O.)
        LANDIF=INT(ANGL1-ANGL2)
        FLANG2=FLANG2+LANDIF
        IF(FLANG2.GT.360)FLANG2=FLANG2-360
        IF(FLANG2.LE.O)FLANG2=360+FLANG2
        END IF
        IF(DISTS2.NE.O.)
        SANDIF=INT(ANGS1-ANGS2)
        SLANG2=SLANG2+SANDIF
        IF(SLANG2.GT.360)SLANG2=SLANG2-360
        IF(SLANG2.LE.O)SLANG2=360+SLANG2
        END IF
        IF(LFLG.EQ.2)
        FLANG3=FLANG3+LANDIF
        SLANG3=SLANG3+LANDIF
        IF(FLANG3.GT.360)FLANG3=FLANG3-360
        IF(FLANG3.LE.O)FLANG3=360+FLANG3
        IF(SLANG3.GT.360)SLANG3=SLANG3-360
        IF(SLANG3.LE.O)SLANG3=360+SLANG3
        A=O.
        IF(FLW(K,I-2).EQ.K3)
        A=A+1.
        FUVEL3=O.
        FVVEL3=O.
        END IF
        CALL MID(DISTL1,DISTL2,DISTL3,IFLG,FUVEL2,FVVEL2,A)
        IF(IFLG-1)311,350,311
311     IF(FLW(K,I-1).EQ.K3)
        A=A+1.
        FUVEL2=O.
        FVVEL2=O.
        END IF
350     IF(FLW(K,I).EQ.K3)
        A=A+1.
        FUVEL1=O.
        FVVEL1=O.
        END IF
        IF(A.EQ.3.)
        FLUVEL=500.
        FLVVEL=500.
        ELSE
```

```
      FLUVEL=(FUVEL1+FUVEL2+FUVEL3)/(3.0-A)
      FLVVEL=(FVVEL1+FVVEL2+FVVEL3)/(3.0-A)
      END IF
      B=0.
      IF(SFW(K,I-2).EQ.K3)
      B=B+1.
      SUVEL3=0.
      SVVEL3=0.
      END IF
      CALL MID(DISTS1,DISTS2,DISTS3,IFLG,SUVEL2,SVVEL2,B)
      IF(IFLG-1)302,351,302
302   IF(SFW(K,I-1).EQ.K3)
      B=B+1.
      SUVEL2=0.
      SVVEL2=0.
      END IF
351   IF(SFW(K,I).EQ.K3)
      B=B+1.
      SUVEL1=0.
      SVVEL1=0.
      END IF
      IF(B.EQ.3.)
      SFUVEL=500.
      SFVVEL=500.
      ELSE
      SFUVEL=(SUVEL1+SUVEL2+SUVEL3)/(3.0-B)
      SFVVEL=(SVVEL1+SVVEL2+SVVEL3)/(3.0-B)
      END IF
      ELSE
      A=0.
      IF(FLW(K,I-1).EQ.K3)
      A=A+1.
      FUVEL2=0.
      FVVEL2=0.
      END IF
      IF(FLW(K,I).EQ.K3)
      A=A+1.
      FUVEL1=0.
      FVVEL1=0.
      END IF
      IF(A.EQ.2.)
      FLUVEL=500.
      FLVVEL=500.
      ELSE
      FLUVEL=(FUVEL1+FUVEL2)/(2.0-A)
      FLVVEL=(FVVEL1+FVVEL2)/(2.0-A)
      FUVEL3=0.
      FVVEL3=0.
      END IF
      B=0.
      IF(SFW(K,I-1).EQ.K3)
      B=B+1.
      SUVEL2=0.
      SVVEL2=0
      END IF
      IF(SFW(K,I).EQ.K3)
      B=B+1.
      SUVEL1=0.
      SVVEL1=0.
      END IF
      IF(B.EQ.2.)
      SFUVEL=500.
      SFVVEL=500.
      ELSE
      SFUVEL=(SUVEL1+SUVEL2)/(2.0-B)
      SFVVEL=(SVVEL1+SVVEL2)/(2.0-B)
      SUVEL3=0.
      SVVEL3=0.
```

```
      END IF
      END IF
      CALL MAXI(FUVEL1,FUVEL2,FUVEL3,FVVEL1,FVVEL2,FVVEL3,FLMAX)
      CALL MAXI(SUVEL1,SUVEL2,SUVEL3,SVVEL1,SVVEL2,SVVEL3,SFMAX)
      IFLDIR=INT(ATAN2(FLUVEL,FLVVEL)*C1-180.)
      ISFDIR=INT(ATAN2(SFUVEL,SFVVEL)*C1-180.)
      IF(IFLDIR.LE.0)IFLDIR=360+IFLDIR
      IF(ISFDIR.LE.0)ISFDIR=360+ISFDIR
      FLVEL=SQRT(FLUVEL**2+FLVVEL**2)
      SFVEL=SQRT(SFUVEL**2+SFVVEL**2)
      IF(LFLG.EQ.2)
      LFLG=0
      IHSS2=HSS(K,I-2)
      ISLP2=SLP(K,I-2)
      DISTL=((DISTL3+DISTL1)/2.)*C3
      DISTS=((DISTS3+DISTS1)/2.)*C3
      IPLCHG=IHSS2-IHSS1
      IPSCHG=ISLP2-ISLP1
      IF(IPLCHG)399,134,399
399   GRADIL=(DISTL3-DISTL1)*C3
      GRADIS=(DISTS3-DISTS1)*C3
      IF(GRADIL.EQ.0.)
      PWL=-999.
      PWLS=-999.
      PWLM=-999.
      PWLSM=-999.
      ELSE
      PGRADL=IPLCHG/GRADIL
      PWL=FLVEL/PGRADL
      PWLM=FLMAX/PGRADL
      IF(FLVEL.GT.500.)
      PWL=-999.
      PWLM=-999.
      END IF
      PWLS=SFVEL/PGRADL
      PWLSM=SFMAX/PGRADL
      IF(SFVEL.GT.500.)
      PWLS=-999.
      PWLSM=-999.
      END IF
      END IF
      IF(IPSCHG.EQ.0.OR.GRADIS.EQ.0.)
      PWSS=-999.
      PWSSM=-999.
      PGRADS=-9.9999
      GO TO 229
      ELSE
      PGRADS=IPSCHG/GRADIS
      PWSS=SFVEL/PGRADS
      PWSSM=SFMAX/PGRADS
      IF(SFVEL.GT.500.)
      PWSS=-999.
      PWSSM=-999.
      END IF
      END IF
      GO TO 229
      ELSE
      IF(LFLG.EQ 1)
      LFLG=2
      GO TO 134
      ELSE
      IHSS2=HSS(K,I-1)
      ISLP2=SLP(K,I-1)
      DISTL=((DISTL2+DISTL1)/2.)*C3
      DISTS=((DISTS2+DISTS1)/2.)*C3
      IPLCHG=IHSS2-IHSS1
      IPSCHG=ISLP2-ISLP1
      IF(IPLCHG)344,134,344
```

```
344       GRADIL=(DISTL2-DISTL1)*C3
          GRADIS=(DISTS2-DISTS1)*C3
          IF(GRADIL.EQ.O.)
          PWL=-999.
          PWLS=-999.
          PWLM=-999.
          PWLSM=-999.
          ELSE
          PGRADL=IPLCHG/GRADIL
          PWL=FLVEL/PGRADL
          PWLM=FLMAX/PGRADL
          IF(FLVEL.GT.500.)
          PWL=-999.
          PWLM=-999.
          END IF
          PWLS=SFVEL/PGRADL
          PWLSM=SFMAX/PGRADL
          IF(SFVEL.GT.500.)
          PWLS=-999.
          PWLSM=-999.
          END IF
          END IF
          IF(IPSCHG.EQ.O.OR.GRADIS.EQ.O.)
          PWSS=-999.
          PWSSM=-999.
          PGRADS=-9.9999
          GO TO 229
          ELSE
          PGRADS=IPSCHG/GRADIS
          PWSS=SFVEL/PGRADS
          PWSSM=SFMAX/PGRADS
          IF(SFVEL.GT.500.)
          PWSS=-999.
          PWSSM=-999.
          END IF
          END IF
          END IF
          GO TO 229
          END IF
          ELSE
          IF(CODE(K,I).EQ.20)
          BB=.5
          KHH=KHH+1
          IF(KHH.EQ.2.AND.HSS(K,I-1).EQ.O)KHH=1
          DISLLA(I)=O.
          DISLLO(I)=O.
          DISSLA(I)=O.
          DISSLO(I)=O.
          IF(KHH.EQ.1)
          FLANG1=900
          SLANG1=900
          LFLG=O
          KLL=O
          GO TO 134
          END IF
          IF(ISLP1.LT.800)
          FLANG1=900
          SLANG1=900
          GO TO 134
          END IF
          IF(SLP(K,I-1).LT.800.AND.LFLG.EQ.O)
          FLANG1=900
          SLANG1=900
          GO TO 134
          END IF
          DISTL1=O.
          DISTS1=O.
          FLANG1=(FLW(K,I)/K1)*K2
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            SLANG1=(SFW(K,I)/K1)*K2
            IF(LFLG.EQ.2)
            DISTS3=DISTS2
            SLANG3=SLANG2
            END IF
            DISTS2=SQRT(DISSLA(I-1)**2+DISSLO(I-1)**2)
            SLANG2=(SFW(K,I-1)/K1)*K2
            SCKLAT=SCVLAT(J)*C2
            SCKLON=SCVLON(J)*(COS(SCLAT(J)/C1))*C2
            SFVEL2=FLOAT(SFW(K,I-1)-(SFW(K,I-1)/K1)*K1)
            CALL COMP(SFVEL2,SLANG2,C1,SCKLAT,SCKLON,SUVEL2,SVVEL2)
            B=0.
            IF(LFLG.EQ.2)
            SFVEL3=FLOAT(SFW(K,I-2)-(SFW(K,I-2)/K1)*K1)
            CALL COMP(SFVEL3,SLANG3,C1,SCKLAT,SCKLON,SUVEL3,SVVEL3)
            IF(SFW(K,I-2).EQ.K3)
            B=B+1.
            SUVEL3=0.
            SVVEL3=0.
            END IF
            CALL MID(DISTS1,DISTS2,DISTS3,IFLG,SUVEL2,SVVEL2,B)
            IF(IFLG-1)401,453,401
401         IF(SFW(K,I-1).EQ.K3)
            B=B+1.
            SUVEL2=0.
            SVVEL2=0.
            END IF
453         IF(B.EQ.2.)
            SFUVEL=500.
            SFVVEL=500.
            ELSE
            SFUVEL=(SUVEL2+SUVEL3)/(2.0-B)
            SFVVEL=(SVVEL2+SVVEL3)/(2.0-B)
            SUVEL1=0.
            SVVEL1=0.
            END IF
            ELSE
            IF(SFW(K,I-1).NE.K3)
            SFUVEL=SUVEL2
            SFVVEL=SVVEL2
            SUVEL1=0.
            SVVEL1=0.
            SUVEL3=0.
            SVVEL3=0.
            ELSE
            SFUVEL=500.
            SFVVEL=500.
            END IF
            END IF
            CALL MAXI(SUVEL1,SUVEL2,SUVEL3,SVVEL1,SVVEL2,SVVEL3,SFMAX)
            IFLDIR=-1
            ISFDIR=INT(ATAN2(SFUVEL,SFVVEL)*C1-180.)
            IF(ISFDIR.LE.0)ISFDIR=360+ISFDIR
            FLVEL=999.
            SFVEL=SQRT(SFUVEL**2+SFVVEL**2)
            IF(LFLG.EQ.2)
            ISLP2=SLP(K,I-2)
            DISTS=(DISTS3/2.)*C3
            IPSCHG=ISLP2-ISLP1
            IF(IPSCHG)440,134,440
440         GRADIS=DISTS3*C3
            PWL=-999.
            PWLS=-999.
            PWLM=-999.
            PWLSM=-999.
            IF(GRADIS)443,134,443
443         PGRADS=IPSCHG/GRADIS
            CALL BEE(PGRADS,BB)
```

```
          PWSS=SFVEL/PGRADS
          PWSSM=SFMAX/PGRADS
          IF(SFVEL.GT.500.)
          PWSS=-999.
          PWSSM=-999.
          END IF
          GO TO 229
          ELSE
          ISLP2=SLP(K,I-1)
          DISTS=(DISTS2/2.)*C3
          IPSCHG=ISLP2-ISLP1
          IF(IPSCHG)444,134,444
444       GRADIS=DISTS2*C3
          PWL=-999.
          PWLS=-999.
          PWLM=-999.
          PWLSM=-999.
          IF(GRADIS)447,134,447
447       PGRADS=IPSCHG/GRADIS
          CALL BEE(PGRADS,BB)
          PWSS=SFVEL/PGRADS
          PWSSM=SFMAX/PGRADS
          IF(SFVEL.GT.500.)
          PWSS=-999.
          PWSSM=-999.
          END IF
          GO TO 229
          END IF
          ELSE
          BB=.5
          KHH=KHH+1
          IF(KHH.EQ.2.AND.HSS(K,I-1).EQ.0)KHH=1
          DISLLA(I)=0.
          DISLLO(I)=0.
          DISSLA(I)=0.
          DISSLO(I)=0.
          IF(KHH.EQ.1)
          FLANG1=900
          SLANG1=900
          LFLG=0
          KLL=0
          GO TO 134
          END IF
          IF(IHSS1.EQ.0.AND.CODE(K,I-1).EQ.20)IHSS1=HSS(K,I-1)
          IF(IHSS1.EQ.0)
          FLANG1=900
          SLANG1=900
          LFLG=0
          GO TO 134
          END IF
          IF(CODE(K,I-1).NE.20)
          IF(HSS(K,I-1).EQ.0.AND.LFLG.EQ.0)
          FLANG1=900
          SLANG1=900
          GO TO 134
          END IF
          FLANG1=(FLW(K,I)/K1)*K2
          SLANG1=(SFW(K,I)/K1)*K2
          IF(LFLG.EQ.2)
          DISTS3=DISTS2
          SLANG3=SLANG2
          SUVEL3=SUVEL2
          SVVEL3=SVVEL2
          END IF
          DISTS2=DISTS1
          DISTS1=0.
          SLANG2=SLANG1
          SUVEL2=SUVEL1
```

```
      SVVEL2=SVVEL1
      B=O.
      IF(LFLG.EQ.2)
      IF(SFW(K,I-2).EQ.K3)
      B=B+1.
      SUVEL3=O.
      SVVEL3=O.
      END IF
      CALL MID(DISTS1,DISTS2,DISTS3,IFLG,SUVEL2,SVVEL2,B)
      IF(IFLG-1)501,506,501
501   IF(SFW(K,I-1).EQ.K3)
      B=B+1.
      SUVEL2=O.
      SVVEL2=O.
      END IF
506   IF(B.EQ.2.)
      SFUVEL=500.
      SFVVEL=500.
      ELSE
      SFUVEL=(SUVEL2+SUVEL3)/(2.-B)
      SFVVEL=(SVVEL2+SVVEL3)/(2.-B)
      SUVEL1=O.
      SVVEL1=O.
      END IF
      ELSE
      IF(SFW(K,I-1).NE.K3)
      SFUVEL=SUVEL2
      SFVVEL=SVVEL2
      SUVEL1=O.
      SVVEL1=O.
      SUVEL3=O.
      SVVEL3=O.
      ELSE
      SFUVEL=500.
      SFVVEL=500.
      END IF
      END IF
      CALL MAXI(SUVEL1,SUVEL2,SUVEL3,SVVEL1,SVVEL2,SVVEL3,SFMAX)
      ISFDIR=INT(ATAN2(SFUVEL,SFVVEL)*C1-180.)
      IF(ISFDIR.LE.O)ISFDIR=360+ISFDIR
      SFVEL=SQRT(SFUVEL**2+SFVVEL**2)
      IF(SFVEL.GT.500.)SFVEL=999.
      ELSE
      DISTS1=O.
      IF(HSS(K,I-2).EQ.O.AND.LFLG.EQ.O)GO TO 134
      END IF
      IF(LFLG.EQ.2)
      DISTL3=DISTL2
      FLANG3=FLANG2
      END IF
      DISTL1=O.
      FLANG2=FLANG1
      IF(CODE(K,I-1).EQ.20)
      DISTL2=SQRT(DISLLA(I-2)**2+DISLLO(I-2)**2)
      IFLW3=FLW(K,I-3)
      IFLW2=FLW(K,I-2)
      ELSE
      DISTL2=SQRT(DISLLA(I-1)**2+DISLLO(I-1)**2)
      IFLW3=FLW(K,I-2)
      IFLW2=FLW(K,I-1)
      END IF
      IF(LFLG.EQ.2)
      FUVEL3=FUVEL2
      FVVEL3=FVVEL2
      END IF
      FUVEL2=FUVEL1
      FVVEL2=FVVEL1
      A=O.
```

```
         IF(LFLG.EQ.2)
         IF(IFLW3.EQ.K3)
         A=A+1.
         FUVEL3=0.
         FVVEL3=0.
         END IF
         CALL MID(DISTL1,DISTL2,DISTL3,IFLG,FUVEL2,FVVEL2,A)
         IF(IFLG-1)502,552,502
502      IF(IFLW2.EQ.K3)
         A=A+1.
         FUVEL2=0.
         FVVEL2=0.
         END IF
552      IF(A.EQ.2.)
         FLUVEL=500.
         FLVVEL=500.
         ELSE
         FLUVEL=(FUVEL2+FUVEL3)/(2.0-A)
         FLVVEL=(FVVEL2+FVVEL3)/(2.0-A)
         FUVEL1=0.
         FVVEL1=0.
         END IF
         ELSE
         IF(IFLW2.NE.K3)
         FLUVEL=FUVEL2
         FLVVEL=FVVEL2
         FUVEL1=0.
         FVVEL1=0.
         FUVEL3=0.
         FVVEL3=0.
         ELSE
         FLUVEL=500.
         FLVVEL=500.
         END IF
         END IF
         CALL MAXI(FUVEL1,FUVEL2,FUVEL3,FVVEL1,FVVEL2,FVVEL3,FLMAX)
         IFLDIR=INT(ATAN2(FLUVEL,FLVVEL)*C1-180.)
         IF(CODE(K,I-1).EQ.20)
         SFVEL=999.
         ISFDIR=-1
         END IF
         IF(IFLDIR.LE.0)IFLDIR=360+IFLDIR
         FLVEL=SQRT(FLUVEL**2+FLVVEL**2)
         IF(LFLG.EQ.2)
         LFLG=0
         DISTL=(DISTL3/2.)*C3
         DISTS=DISTL
         IF(CODE(K,I-1).EQ.20)
         IHSS2=HSS(K,I-3)
         ELSE
         IHSS2=HSS(K,I-2)
         ISLP2=SLP(K,I-2)
         END IF
         IPLCHG=IHSS2-IHSS1
         IF(IPLCHG)589,134,589
589      GRADIL=DISTL3*C3
         IF(GRADIL)588,134,588
588      PGRADL=IPLCHG/GRADIL
         PWL=FLVEL/PGRADL
         PWLM=FLMAX/PGRADL
         IF(FLVEL.GT.500.)
         PWL=-999.
         PWLM=-999.
         END IF
         PWLS=SFVEL/PGRADL
         PWLSM=SFMAX/PGRADL
         IF(SFVEL.GT.500.)
         PWLS=-999.
```

```
      PWLSM=-999.
      END IF
      IPSCHG=ISLP2-ISLP1
      IF(IPSCHG.EQ.O.OR.CODE(K,I-1).EQ.20)
      PWSS=-999.
      PWSSM=-999.
      PGRADS=-9.9999
      ELSE
      PGRADS=IPSCHG/GRADIL
      CALL BEE(PGRADS,BB)
      PWSS=SFVEL/PGRADS
      PWSSM=SFMAX/PGRADS
      IF(SFVEL-999)229,575,229
575   PWSS=-999.
      PWSSM=-999.
      END IF
      GO TO 229
      ELSE
      DISTL=(DISTL2/2.)*C3
      DISTS=DISTL
      IF(CODE(K,I-1).EQ.20)
      IHSS2=HSS(K,I-2)
      ELSE
      IHSS2=HSS(K,I-1)
      ISLP2=SLP(K,I-1)
      END IF
      IPLCHG=IHSS2-IHSS1
      IF(IPLCHG)554,134,554
554   GRADIL=DISTL2*C3
      IF(GRADIL)582,134,582
582   PGRADL=IPLCHG/GRADIL
      PWL=FLVEL/PGRADL
      PWLM=FLMAX/PGRADL
      IF(FLVEL.GT.500.)
      PWL=-999.
      PWLM=-999.
      END IF
      PWLSM=SFMAX/PGRADL
      PWLS=SFVEL/PGRADL
      IF(SFVEL.GT.500.)
      PWLS=-999.
      PWLSM=-999.
      END IF
      IPSCHG=ISLP2-ISLP1
      IF(IPSCHG.EQ.O.OR.CODE(K,I-1).EQ.20)
      PWSS=-999.
      PWSSM=-999.
      PGRADS=-9.9999
      ELSE
      PGRADS=IPSCHG/GRADIL
      CALL BEE(PGRADS,BB)
      PWSS=SFVEL/PGRADS
      PWSSM=SFMAX/PGRADS
      IF(SFVEL-999.)229,576,229
576   PWSS=-999.
      PWSSM=-999
      END IF
      GO TO 229
      END IF
      END IF
      END IF
      GO TO 12
229   N1=N1+1
      PWSL=-999.
      PWSLM=-999.
      WRITE(18,123)DISTL,DISTS,PWL,PWSS,PWLM,PWSSM,PWLS,PWLSM,
      PWSL,PWSLM
134   WRITE(17,5)CODE(K,I),TIME(K,I),LAT(K,I),LON(K,I),FLANG1,
```

```
     .   FLVEL1,HSS(K,I),SLANG1,SFVEL1,SLP(K,I)
196      IF(ISLP1-800)12,199,199
199      IF(SLANG1.NE.900.OR.FLANG1.NE.900)
         IF(ISLP1.GT.IPE.AND.DISTS1.GT.DISTP)
         IF(FLVEL1.GE.35..OR.SFVEL1.GE.25.)
         IPE=ISLP1
         DISTM=DISTS1
         DISTP=DISTS1
         ISLPM=2000
         END IF
         ELSE
         IF(FLVEL1.GE.35..OR.SFVEL1.GE.25.)
         IF(DISTS1.GT.DISTP)DISTP=DISTS1
         ELSE
         IF(DISTS1.LT.DISTN.AND.DISTS1.GT.DISTP)
         IF(FLVEL1.LT.25..AND.SFVEL1.LT.20.)
         IPE=ISLP1
         DISTM=DISTS1
         DISTN=DISTS1
         ISLPM=2000
         END IF
         END IF
         END IF
         END IF
         END IF
         IF(BB.GT.O..AND.DISTS1.GT.DISTM)
         IF(ISLP1.LT.ISLPM.AND.ISLP1.GT.800)
         DISTM=DISTS1
         DISTO=DISTS1
         IF(IPE.EQ.1008)
         IPED=INT(2.27*ABS(SIN((TIME(K,I)*180.)/(720*C1))))
         IPE=IPE-IPED
         END IF
         IF(TIME(K,I).GT.SCMIN(JJ))
         ISCSLP=SCSLP(JJ)
         ELSE
         CC=FLOAT(SCMIN(J)-TIME(K,I))
         DD=FLOAT(SCMIN(J)-SCMIN(J-1))
         RAT=CC/DD
         ISCSLP=SCSLP(J)-INT(RAT*(SCSLP(J)-SCSLP(J-1)))
         END IF
         IF(LAT(K,I).LE.30.)
         IPN=1027-INT(COS(LAT(K,I)*3./C1)*17.)
         ELSE
         IPN=1027+INT(COS(LAT(K,I)*3./C1)*17.)
         END IF
         IF(IPN-IPE.LT.3)IPN=IPE+3
         IF(IPN-ISLP1.LT.3)IPN=ISLP1+3
         EE=FLOAT(IPN-ISCSLP)
         FF=FLOAT(ISLP1-ISCSLP)
         IF(IPE.GT.ISCSLP.AND.ISLP1.GT.ISCSLP)
         AA=(DISTS1**BB)*(ALOG(EE/FF))
         GG=FLOAT(IPE-ISCSLP)
         RS=(AA/(ALOG(EE/GG)))**(1./BB)*C3
         IF(ISLP1.GE.IPE)ISLPM=ISLP1
         END IF
         END IF
         END IF
 12    CONTINUE
       IF(DISTM.NE.DISTO)RS=DISTM*C3
       IF(DISTP*C3.GT.RS)RS=DISTP*C3
       WRITE(19,198)NUM(K),N(K),RS,IPE,IPN,N1
198    FORMAT(1X,I7,1X,I2,1X,F5.0,1X,I4,1X,I4,1X,I2)
       KLL=0
       KHH=0
 13  CONTINUE
     GO TO 98
 99  STOP
```

```
      END

      SUBPROGRAMS*****************************************************

      MINUTE**************

      THIS SUBPROGRAM CONVERTS CODED TIME TO A FORMAT THAT IS A CONTIN-
      UOUS MINUTE STARTING AT 0000Z ON THE FIRST DAY OF DATA ON A PARTI-
      CULAR STORM. THIS ASSISTS IN COMPUTATIONS REQUIRING TIME DIFFEREN-
      CES (SYSTEM VELOCITIES, ETC.).

      VARIABLE LIST***

      MIN1 - MINUTE REMAINDER

      SUBROUTINE MINUTE(ITIM,MIN)
      MIN=0
      MIN1=ITIM
100   MIN1=MIN1-10000
      IF(MIN1-2400)200,600,600
600   MIN=MIN+1440
      GO TO 100
200   IF(MIN1-100)300,700,700
700   MIN=MIN+60
      MIN1=MIN1-100
      GO TO 200
300   MIN=MIN+MIN1
      RETURN
      END

      VEL***************

      THIS SUBPROGRAM TAKES THE CHANGES IN LATITUDE AND LONGITUDE BE-
      TWEEN CONSECUTIVE FIXES AND COMPUTES THE RESULTING SYSTEM VELOCITY.

      VARIABLE LIST***

      DIFLAT - CHANGE IN LATITUDE
      DIFLON - CHANGE IN LONGITUDE
      ITIDIF - TIME DIFFERENCE
      HLAT1 - DUMMY ARGUMENT
      HLON1 - DUMMY ARGUMENT
      MIN2 - DUMMY ARGUMENT
      VELLAT - DUMMY ARGUMENT
      VELLON - DUMMY ARGUMENT

      SUBROUTINE VEL(TLAT,TLON,MIN,HLAT1,HLON1,MIN2,VELLAT,VELLON)
      DIFLAT=TLAT-HLAT1
      DIFLON=TLON-HLON1
      ITIDIF=MIN-MIN2
      HLAT1=TLAT
      HLON1=TLON
      MIN2=MIN
      VELLAT=DIFLAT/ITIDIF
      VELLON=DIFLON/ITIDIF
      RETURN
      END

      EXCH***************

      THIS SUBPROGRAM EXCHANGES FIX VALUES SO THAT THEY CAN BE USED AS
      PAST POSITIONS AND TIMES WHEN THE NEXT FIX IS EVALUATED.

      SUBROUTINE EXCHG(TLAT,SLAT1,TLON,SLON1,MIN,MIN2)
      SLAT1=TLAT
      SLON1=TLON
      MIN2=MIN
      RETURN
```

```
      END

      COMP****************

      THIS SUBPROGRAM SEPARATES THE OBSERVED WIND INTO U AND V COMPO-
      NENTS. THE SYSTEM MOTION (U,V) COMPONENTS ARE THEN SUBTRACTED TO
      ADJUST THE WIND FOR SYSTEM MOTION.

      VARIABLE LIST***

      FLVEL - DUMMY ARGUMENT
      FUVEL - DUMMY ARGUMENT
      FVVEL - DUMMY ARGUMENT
      IFLANG - DUMMY ARGUMENT

      SUBROUTINE COMP(FLVEL,IFLANG,C1,SCKLAT,SCKLON,FUVEL,FVVEL)
      IF(IFLANG.EQ.900)
      FUVEL=0.
      FVVEL=0.
      ELSE
      FUVEL=FLVEL*(-SIN(IFLANG/C1))-SCKLON
      FVVEL=FLVEL*(-COS(IFLANG/C1))-SCKLAT
      FLVEL=SQRT(FUVEL**2+FVVEL**2)
      IF(FUVEL.EQ.0..AND.FVVEL.EQ.0.)
      IFLANG=900
      ELSE
      IFLANG=INT(ATAN2(FUVEL,FVVEL)*C1-180.)
      END IF
      END IF
      IF(IFLANG.LE.0)IFLANG=360+IFLANG
      RETURN
      END

      MID****************

      THIS SUBPROGRAM CHECKS INTERMEDIATE WIND INFORMATION THAT DOES NOT
      HAVE PRESSURE DATA FOR INTERMEDIATE DISTANCE BETWEEN THOSE WITH
      PRESSURE DATA.

      SUBROUTINE MID(DISTL1,DISTL2,DISTL3,IFLG,FUVEL2,FVVEL2,A)
      IFLG=0
      IF(DISTL2.LT.DISTL1.AND.DISTL2.LT.DISTL3)GO TO 400
      IF(DISTL2.GT.DISTL1.AND.DISTL2.GT.DISTL3)GO TO 400
      GO TO 500
400   A=A+1.
      FUVEL2=0.
      FVVEL2=0.
      IFLG=1
500   RETURN
      END

      MAXI***************

      THIS SUBPROGRAM DETERMINES THE MAXIMUM WIND BETWEEN OBSERVATIONS
      WITH PRESSURE DATA AFTER TRANSPOSITION AND WITH SYSTEM MOTION
      EFFECTS ELIMINATED.

      SUBROUTINE MAXI(FUVEL1,FUVEL2,FUVEL3,FVVEL1,FVVEL2,FVVEL3,FLMAX)
      FLVEL1=SQRT(FUVEL1**2+FVVEL1**2)
      FLVEL2=SQRT(FUVEL2**2+FVVEL2**2)
      FLVEL3=SQRT(FUVEL3**2+FVVEL3**2)
      FLMAX=AMAX1(FLVEL1,FLVEL2,FLVEL3)
      RETURN
      END

      BEE****************

      THIS SUBPROGRAM COMPUTES THE "BB" SCALING PARAMETER USED IN THE
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ANALYTIC MODEL OF RADIAL SLP PROFILES OF TROPICAL CYCLONES. IT
MAKES USE OF THE INNERMOST (CORE REGION) SLP GRADIENT.

VARIABLE LIST***

P - TEMPORARY VALUE OF PGRADS

SUBROUTINE BEE(PGRADS,BB)
P=PGRADS
IF(P.GT.3.5)P=3.5
BB=(((P*2.)/3.5)+.5)
RETURN
END
```

VITA

Charles B. Stanfield was born in West Palm Beach, Florida on 6 October 1952 to Charles M. and Nancy M. Stanfield. He was raised in Lake Worth, Florida where he attended grade school and later graduated from Lake Worth Senior High School in 1971. In that same year he entered Florida State University from which he graduated in 1975 with a Bachelor of Science Degree in Meteorology and as a commissioned Second Lieutenant in the United States Air Force.

His first assignment was Detachment 7, 15th Weather Squadron at Kelly Air Force Base in San Antonio, Texas where in addition to forecasting he held the positions of Radar Officer and Staff Weather Assistant. From Kelly, he was assigned to Andersen AFB, Guam as an Aerial Reconnaissance Weather Officer (ARWO) for Detachment 4, Headquarters Air Weather Service and the 54th Weather Reconnaissance Squadron. While there, he logged over 1100 hours of flying time and 45 typhoon penetrations. He also held the positions of Chief of Aircrew Training, Standardization and Evaluation Flight Examiner, and Chief ARWO.

The author entered Texas A&M University in January 1982 to pursue the degree of Master of Science in Meteorology under the auspices of the Air Force Institute of Technology. He is currently serving as Scientific Services Officer for 5th Weather Squadron, Ft. McPherson, Georgia.

He is married to the former Alma Villarreal of San Antonio, Texas, and they have two sons, Charles Jr. and Brenton. His permanent mailing address is 1222 North O Street, Lake Worth, Florida 33460.

END
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DTIC